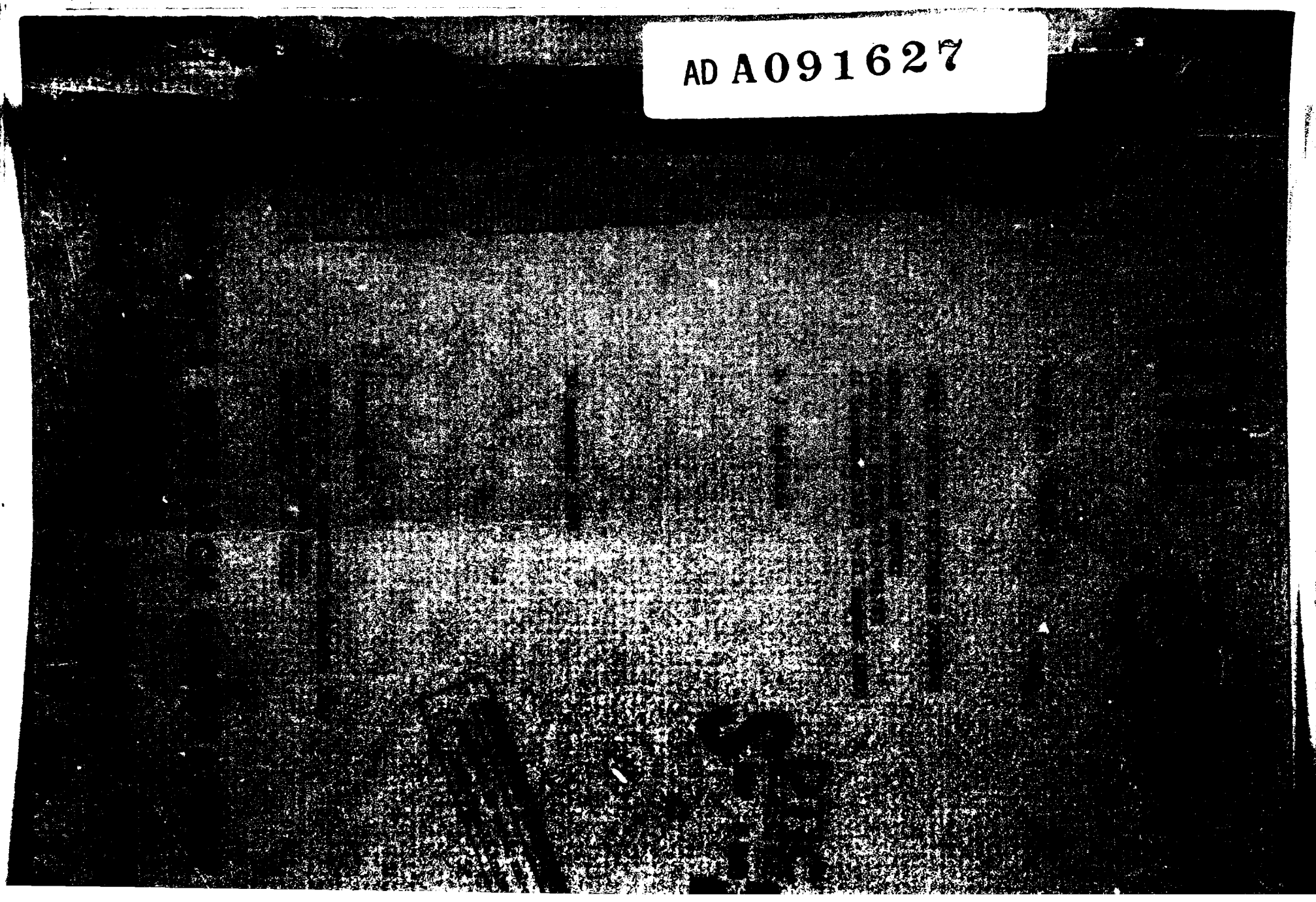
AD-A091 627 CALIFORNIA UNIV BERKELEY ELECTRONICS RESEARCH LAB F/G 20/3
JOINT SERVICES ELECTRONICS PROGRAM.(U)
SEP 80 D J ANGELAKOS F49620-79-C-0178
UNCLASSIFIED UCB/ERL-80/1 NL



JOINT SERVICES ELECTRONICS PROGRAM

ANNUAL PROGRESS REPORT (CONTRACT F49620-79-C-0178)

1 September 1979 - 31 August 1980

by

D.J. Angelakos

Report No. UCB/ERL 80/1

30 September 1980

ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley CA 94720

(1) Annual progress rpt. (Final) 1 Sep 79 - 31 Aug

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (1)	2. GOVT ACCESSION NO. AD-A091627
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) JOINT SERVICES ELECTRONICS PROGRAM, Final/Progress Report	5. TYPE OF REPORT & PERIOD COVERED ANNUAL 1 September '79-31 August '80
(14)	6. PERFORMING ORG. REPORT NUMBER UCB/ERL-80/1
7. AUTHOR(s) (10) D. J. Angelakos	8. CONTRACT OR GRANT NUMBER(s) Contract F49620-79-C-0178
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electronics Research Laboratory College of Engineering, University of California Berkeley, CA 94720	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2305/B1
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research (AFSC) Bolling Air Force Base, DC 20332	(11) 12. REPORT DATE 30 September 1980
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DTIC ELECTE NOV 5 1980 S C

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electromagnetics, solid state electronics: materials and devices, quantum electronics, information and control systems, circuits.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An annual report of the JSEP (Joint Services Electronics Program) in Electromagnetics, Solid State Electronics, Materials and Devices, Quantum Electronics and Information Sciences is presented. In addition, results of the research to date are summarized and significant accomplishments are indicated.

12/553 SCD

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

1. INTRODUCTION

During the period 1 May 1980 through 30 April 1981, the Electronics Research Laboratory (ERL), University of California, Berkeley, is receiving support for its basic program from the Joint Services Electronics Program (JSEP), sponsored by the Departments of the Air Force (Air Force Office of Scientific Research), Army(Army Research Office), and Navy (Office of Naval Research), under contract F49620-79-C-0178.

This annual report is an updating report; hence it covers the period 1 September 1979 through 31 August 1980. Significant Accomplishments, where applicable, appear in the project reports (section A). In particular, the three most significant accomplishments, as determined by the Director, are summarized as:

i. Project EM-81-1 - Multiple Scattering of Conducting Bodies

We have positively demonstrated that the Unimoment Method we have developed is adaptable to multiple scattering of arbitrary shaped scatterers. The computation is also proven to be accurate and economical. The results are contained in a PhD thesis submitted by Dr. John F. Hunka, entitled, "Electromagnetic scattering by two bodies of revolution."

ii. Project SSD-81-1 - Advanced Lithographic Techniques for Microcircuits

A breakthrough in the problem of negative resist swelling and its inherent electron beam resolution has been made. We have demonstrated that a non-swelling positive photoresist (AZ1350J) may be used as a negative electron resist by means of image reversal. Resolution below 1 μm in films 1.2 μm thick was observed at a dose of 25 $\mu C/cm^2$ at 20keV. The high etch resistance in plasma etching is also retained.

iii. Project ISS-81-3 - Computer Optimization of Electronic Circuits

The significant accomplishments of our research can be summarized as follows: a) We have developed a prototype interactive, optimization based computer aided design package, capable of accepting semi-infinite constraints on frequency and time responses, but not tolerancing or post manufacturing tuning. This package serves as a test bed for the development of ideas and concepts for a much more sophisticated package which is now being constructed. b) We have shown that device models can be obtained which make it practical to solve the optimal design centering, tolerancing and tuning problem. c) We have developed a number of optimization and inequality solving algorithms for computer aided design which either solve problems that were hitherto unsolvable, or which converge much more rapidly than currently available algorithms.

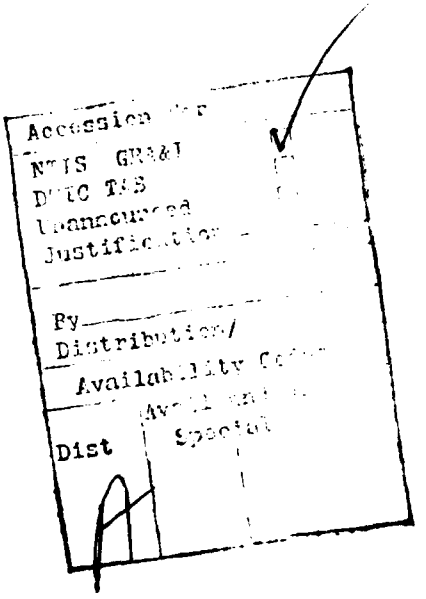
Further: the paper by D. J. Allstot, R. W. Brodersen and P. R. Gray entitled, "MOS switched capacitor ladder filters," IEEE Jour. Solid-State Circuits, vol. SC-13, no. 6, Dec. 1978, pp. 806-814, received the 1980 IEEE W. R. G. Baker Prize Paper award. The work reported was supported in part by JSEP.

The report contains:

A. 1980-1981 JSEP Projects: as of 31 August 1980

B. Consolidated List of Published JSEP Papers through 31 August 1980

During this time period 1 September 1979 - 31 August 1980, there are currently an additional 14 papers being processed: in press, in review, submitted and being prepared. Further, there have been 13 Conference papers presented (or to be presented).



2. RESEARCH PROJECTS

Project No.	Title	Faculty Investigator(s)

A. 1980-1981 JSEP Projects: as of 31 August 1980

I. ELECTROMAGNETICS

EM-81-1	Multiple Scattering of Conducting Bodies	D. J. Angelakos K. K. Mei
EM-81-2 (terminating in part)	Infrared and Optical Antennas and Guides	D. J. Angelakos K. K. Mei S. E. Schwarz

II. SOLID STATE ELECTRONICS

A. Materials

SSM-81-1 (terminating)	Lifetime Studies in Ion-Implanted Semiconductors	C. Hu W. G. Oldham
SSM-81-2	Compound Semiconductors: Material-Property and Device Studies	C. Hu S. Wang
SSM-81-3	Molecular Beam Epitaxy & Its Application to Studies of Materials Aspects of Microstructure Engineering	S. Wang C. Hu

B. Devices

SSD-81-1	Research in Advanced Lithographic Techniques for Microcircuits	A. R. Neureuther W. G. Oldham
SSD-81-2	Fundamental Limitations of Miniaturization of Josephson Memory & Logic Circuits	T. Van Duzer
SSD-81-3 (terminating)	New Integrated Circuit Processes for High Performance LSI	D. A. Hodges W. G. Oldham
SSD-81-4	Basic Research in Wide-Dynamic Range, Low Noise Amplification Using Monolithic Integrated-Circuit Technology	R. W. Brodersen P. R. Gray R. G. Meyer D. O. Pederson

RESEARCH PROJECTS - continued

Project No.	Title and Faculty Investigator(s)	
II. SOLID STATE ELECTRONICS, concluded		
B. Devices, concluded		
SSD-81-5	Research on Electronic Systems Composed of Polymer Films and Planar Devices for Transducer Applications	D. W. Hess R. S. Muller
III. QUANTUM ELECTRONICS		
QE-81-1	Thin-Film and Guided-Wave Active Optical Devices	S. Wang T. K. Gustafson J. R. Whinnery
QE-81-2	Millimeter & Infrared Heterodyne Mixing & Detection	T. K. Gustafson S. E. Schwarz T. Van Duzer
IV. INFORMATION SYSTEMS		
ISS-81-1	Large-Scale and Non-Linear Circuits Study	L. O. Chua E. S. Kuh
ISS-81-2	Control of Large Systems	C. A. Desoer P. P. Varaiya
ISS-81-3	Computer Optimization of Electronic Circuits	R. G. Meyer E. Polak A. Sangiovanni-Vincentelli
ISS-81-4 (terminating)	VLSI Circuits for Future Computing Systems	A. M. Despain D. A. Patterson C. H. Sequin
ISS-81-5 (terminating in part)	Analog Adaptive Filters for Speech Processing	R. W. Brodersen D. G. Messerschmitt
ISS-81-6 (terminated)	An Analytical Characterization of Image Objects	D. J. Sakrison

B. Consolidated List of Published JSEP Papers through 31 August 1980

A. 1980-1981 JSEP PROJECTS:

AS OF 31 AUGUST 1980

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

I. Basic Research in Electromagnetics — Coordinator: Professor K. K. Mei

Basic research in electromagnetics at ERL presently consists of two parts. One is the development and application of computational techniques to electromagnetics, and the other is the basic research in theory and experimentation of electromagnetics at infrared frequencies. These two research activities are described in the following.

Computations in Electromagnetics

Research in electromagnetic theory was traditionally done within the regime of applied mathematics. Since the advent of high speed digital computers, we have seen more and more emphasis on the computational research being done in applied electromagnetics. In the early 1960's the main thrust of electromagnetic related computation was in integral equation approaches.[1] The integral equation was a natural choice in radiation problems because the radiation conditions at infinity could easily be satisfied by using proper Green's functions. Although the integral equation method is not too well adapted to problems involving fat bodies and dielectric bodies, early investigators were still quite happy with it, because even with its limitations it was possible to solve many problems which were hitherto unsolvable. As more and more problems were solved, researchers began to look for alternatives to the integral equation approach, which might be better than the integral equation method in solving fat, dielectric or even inhomogeneous bodies. This effort is represented by the unimoment method which was developed by K. K. Mei and his associates at ERL[2], and the several publications that follow[3,4] indeed show that the differential equation approach can be very efficient in regions where the integral equation method is clumsy and impractical. This method is currently being used to investigate the scattering by buried dielectric obstacles, a project now supported outside the JSEP.

The unimoment method is not only good in solving scattering by dielectric bodies, it is also an excellent technique for solving scattering by perfectly conducting bodies. A simple illustration shows how it works. Consider the scattering by a conducting spheroid as shown in Fig. 1. Outside a circumscribing sphere, the solution is expressed in classical spherical harmonics with undetermined coeffecients, and inside the sphere the solutions are generated by solving the finite element equations. The expansion coefficients on both sides of the sphere are determined by enforcing the continuity conditions on the sphere. It is interesting to see that the finite element mesh area becomes larger if the spheroid becomes thinner, and it becomes smaller if the spheroid becomes fat. That means the unimoment method is more efficient (more precise) for a fat scattering than a skinny scatterer. The integral equation method works just the opposite way, i.e., the surface area of the scatter increases as the scatter becomes fatter and hence requires more computation.

We have already succeeded in using the unimoment method to solve scattering by dielectric bodies[5], and it is apparent that it should work even better when applied to a single fat metal scatterer. So, in the JSEP we decide to apply it to scattering by multiple bodies, and initial success is already observed[6]. A summary of this paper follows.

Numerical codes utilizing the unimoment technique (K. K. Mei, IEEE Trans. Ant. & Prop., AP-22, 760-766, Nov. 1974) have been developed which compute the scattering by metal and inhomogeneous dielectric bodies of revolution. The research described in this paper uses these codes to solve the two-body scattering problem. First, interior field solutions (i.e. interior to the unimoment surface) for each scatterer are solved with the unimoment routines and stored in the form of system solution matrices. These matrices contain the "individual isolated scatterer information" for each scatterer and this information need be obtained only once for each scatterer. Second, an iterative scheme is used to solve for the scattering coefficients for each successive scattering. Rotation and translation addition theorems are employed to rotate and translate incident and scattered fields between coordinate systems for each scatterer. The iterative scheme has been tested on the special case of two perfectly conducting spheres and has proven to be well behaved and accurate. (Presented at USNC/URSI Meeting at Boulder, Colorado, November, 1978.)

Other applications of our computational skill are considerable, but we only wish to investigate fundamental problems. One of the fascinating problems is that of the infrared and optical antennas. At optical frequencies the material behaves very differently from its known properties at microwave frequencies. The computational skill we have developed for dielectric bodies can be used to obtain physical insight into the operation of infrared antennas. It will be used to verify experimental observations and to provide design data to improve such antennas.

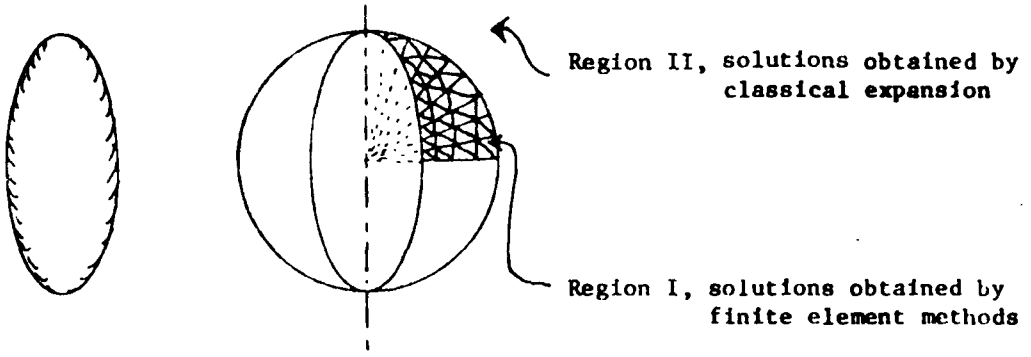


Fig. 1. Finite element meshes used to solve scattering by a spheriod

The scattering by two bodies of different shapes has been shown to be successful. The results are now available[7,8]. However, the two body configurations are still limited to the case that the two bodies do not penetrate the terminating spheres. We are working to remove this limitation.

Electromagnetics at Infrared and Optical Frequencies

Radio, microwave, and light are all electromagnetic waves. The only difference between them is the frequency. However, both in theory and application they are dealt with quite differently. For example, the guided transmission of radio is mostly done by coaxial lines, of microwave by metal waveguides, and of light by beams or dielectric waveguides. There are borderline frequencies where different transmission methods can be used. That indeed is the case at sub-millimeter wave to low infrared waves. Of particular interest is the utilization of metal as a guiding system at low infrared region. It is understood that metal is highly lossy at such frequencies, however, it still has the unique ability of concentrating electromagnetic power to a very small region, much smaller than a wavelength, which is highly desirable for detection. In this part of electromagnetic research we shall study the scattering by impurities and transmission in optical fibres, the application of metal as antennas, and field coupling from dielectric to metal waveguide at low infrared frequencies. It is worth noting that all the technology developed in this study will eventually be applicable to millimeter waves also.

References

[1] Mei, K. K., "On the integral equations of thin wire antennas," IEEE Trans. on Antennas and Propagation, Vol. AP-13, No. 3, pp. 374-378, May 1965.

[2] Mei, K. K., "Unimoment method of solving antenna and scattering problems," IEEE Trans. on Antennas and Propagation. Vol. AP-22, No. 6, pp. 760-766, November 1974.

[3] Stovall, R. and K. K. Mei, "Application of a Unimoment Method to a biconical antenna with inhomogeneous dielectric loading," IEEE Trans. on Antennas and Propagation, Vol. AP-23, No. 3, pp. 335-342, May 1975.

[4] Chang, S. K. and K. K. Mei, "Application of the Unimoment Technique to electromagnetic scattering by dielectric cylinders," IEEE Trans. on Antennas and Propagation, Vol. AP-24, No. 1, January 1976.

[5] Morgan, M., "Numerical computation of electromagnetic scattering by inhomogeneous dielectric bodies of revolution," Ph.D. Dissertation, University of California, Berkeley, 1976.

[6] Hunka, J. F. and K. K. Mei, "Numerical computation of electromagnetic scattering by two bodies of revolution," to be presented at USNC/URSI Meeting, November, 1978, Boulder, Colorado.

[7] Hunka, John F., "Scattering by two bodies of revolution," Ph.D. dissertation, University of California, Berkeley, 1979.

[8] Mei, K. K., J. F. Hunka and S. K. Chang, "Recent developments of the unimoment method," presented at the International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. Also to be published in Recent Developments in Classical Scattering, edited by V. K. Varaden, Academic Press.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: EM-81-1 — Last Year's No.(s): EM-80-1

Title: Multiple Scattering of Conducting Bodies

Senior Principal Investigators(s): D. J. Angelakos (415) 642-7200
K. K. Mei 2-4106

Scientific Objective

Multiple scattering of conducting bodies is a problem of both academic and practical interest. The knowledge of multiple scattering will help many design techniques in microwaves; it may also provide insight into many physical phenomena in field theories. However, scattering by electromagnetic wave is a difficult problem even without the complication of multiple scattering. Recent development of the Unimoment Method has advanced the art of scattering-related computation to fairly large sized three dimensional scatterers[1]. One interesting extension of the new method is to solve the problem of multiple scattering.

The objective of this program is to solve the scattering of two metal bodies of revolution. The geometries of the two scatterers could be different and the distance between them arbitrary. The illuminating plane wave could be arbitrarily oriented and polarized. The bistatic scatterings of the two body scatterings will be our computational objective.

Because of the difficulties involved in theoretical verification of the computation, an experimental study of the multiple scattering will be an integral part of the program.

State of the Art

Scattering by two spheres was first investigated by Trinks[3] in 1935, and then by Germogenova[4] in 1963, for small spheres. Scattering by two arbitrarily shaped bodies was treated by Zitron and Karp[5] and was limited to objects separated far apart. The latest attempt to solve the two sphere scattering problem rigorously was by Liang and Lo[6]. While the multiple scattering mechanism was presented by Zitron and Karp[5] for arbitrarily shaped obstacles, they can only obtain results for scalar fields. In our proposed program, the limitation on the objects is that they be axially symmetric, in addition to the unavoidable limitation of size (diameter less than 2λ).

Progress and Publications Since Last Major Proposal

1. Experimental System

Considerable experimental results have been obtained on high-frequency scattering by multiple spheres.[7] These were primarily back scatter measurements because bistatic measurements involved considerable difficulties; consequently a refinement of the equipment was undertaken.

A semi-automated radar cross-section measurement system has been developed where it is possible to obtain scattering data to be used as verification of the numerical results. The system consists of an indoor image ground plane with a CW microwave system operating in the x-band. It utilizes the well-known null balance technique for extracting the scattered field. A process computer is linked to the system via a network analyzer which is used as a coherent detector. The measurement system employs a reciprocal measurement technique (RMT) which enables one to obtain bistatic scattering data.[2] The process computer stores and removes inherent errors in the system and processes the data in a variety of formats.

The measurement system has proven successful in verifying previous numerical analysis endeavors.[1] The accuracy of the system has been shown to be reliable for cross-sections on the order of $\sigma/\lambda^2 \sim 1$.

2. Computation

The program of scattering by two metal bodies of revolution has been completed.[8,9]

Progress and Publications Since Last Major Proposal

A. Under JSEP

J. F. Hunka, "Electromagnetic scattering by two bodies of revolution," Ph.D. dissertation, University of California, Berkeley, 1979.

K. K. Mei, J. F. Hunka and S. K. Chang, "Recent developments of the unimoment method," International Symposium on Recent Developments in Classical Scattering, Columbus, Ohio, June 1979. To be published as a chapter in Recent Developments in Classical Scattering, edited by V. K. Varadan, Academic Press.

J. F. Hunka and K. K. Mei, "Scattering by two bodies of revolution," IEEE Antennas and Propagation Symposium and URSI/USNC 1980 meeting, Quebec City, Canada, June 1980.

B. Under Other Sponsorship

H. Kao and K. K. Mei, "Scattering by advanced composite bodies of revolution," USNC/URSI Conference, Seattle, Washington, June 1979.

S. Coen and K. K. Mei, "Inverse scattering of layered media," USNC/URSI Conference, Seattle, Washington, June 1979.

S. K. Chang and K. K. Mei, "Generalized Sommerfeld Integrals and Field Expansions in Two-Medium Half-Spaces," IEEE Trans. on Antennas and Propagation, vol. A p. 28, No. 4 pp. 504-512, July 1980.

Significant Accomplishments

We have positively demonstrated that the Unimoment Method we have developed is adaptable to multiple scattering of arbitrary shaped scatterers. The computation is also proven to be accurate and economical. The results are contained in a Ph.D. thesis submitted by Dr. John F. Hunka, entitled "Electromagnetic scattering by two bodies of revolution."

Abstract

Powerful numerical programs have been developed utilizing Mei's Unimoment method which can solve for the electromagnetic scattering by metal and/or inhomogeneous dielectric bodies of revolution. The purpose of this research is to use these existing programs to solve the general three dimensional two-body-of-revolution scattering problem, thereby extending the unimoment technique to include a class of problems not axially symmetric. This extension

of the technique and the experience gained in solving the two body problem may soon enable the analysis of the N-body of revolution problem and eventually develop the capability to compute the scattering by complex composite structures made up of many simple bodies of revolution.

This dissertation presents a systematic procedure for solving the two body of revolution scattering problem by interfacing with a unimoment program. This research presents a detailed investigation of spherical vector wave function expansions and addition theorems. A scatterer-independent, modal incident field formulation is developed as a means of interfacing the multiple scattering and unimoment programs. Also, an experimental scattering measurement system is used for the verification of the multiple scattering computations.

An iterative or "successive scattering" approach is used whereby the scattered field from one body is used as an incident field for the other scatterer. The process mandates the need for suitable field expansions and change of bases for representing fields in the coordinate systems describing the two bodies. To this end, spherical vector wave expansions and rotational and translational addition theorems are developed. For each iteration, the scattering coefficients are computed by a system matrix operation on the known incident field coefficients. The system matrix is generated by the unimoment program only once for each scatterer and contains all the geometrical and electrical properties of the scatterer. A scattered energy criteria is established to terminate the iteration process.

The verification of the multiple scattering program both numerically and experimentally is discussed in depth. Selected case studies of two body configurations are presented to demonstrate the utility of the program and to lay a foundation for future study and analysis.

References

[1] M. Morgan, "Numerical Computation of Electromagnetic Scattering by Inhomogeneous Dielectric Bodies of Revolution," Ph.D. Dissertation, University of California, Department of Electrical Engineering and Computer Sciences, 1976.

[2] J. F. Hunka, R. E. Stoval and D. J. Angelakos, "A Technique for the Rapid Measurement of Bistatic Radar Cross-Sections," IEEE Trans. on Ant. & Prop., Vol. AP-25, No. 2, March 1977, pp. 243-248.

[3] W. Trinks, "Zur Vielfachstreung an Kleinen Kugeln," Ann. Phys., Dtsch. 22, 1935, pp. 561-590.

[4] O. A. Germogenova, "The Scattering of a Plane Electromagnetic Wave By Two Spheres," Akad. Nauk SSSR, Izvestiia, Ser. Geofiz., No. 4, 1963, pp. 648-653.

[5] N. Zitron and S. N. Karp, "High-order Approximations in Multiple Scattering, II, Three Dimensional Scalar Case," J. Math. Phys. 2, No. 3, 1961, pp. 402-406.

[6] C. Liang and Y. T. Lo, "Scattering by Two Spheres," Radio Science, Vol. 2, No. 12, 1967, pp. 1481-1495.

[7] D. J. Angelakos and N. Kumagai, "High Frequency Scattering by Multiple Spheres," IEEE Trans. on Ant. & Prop., Vol. AP-12, No. 1, January 1964, pp. 105-109.

[8]J. F. Hunka and K. K. Mei, "Scattering by two bodies of revolution," IEEE Antennas and Propagation Symposium and URSI/USNC 1980 meeting, Quebec City, Canada, June 1980.

[9]S. K. Chang and K. K. Mei, "Generalized Sommerfeld Integrals and Field Expansions in Two-Medium Half-Spaces," IEEE Trans. on Antennas and Propagation, vol. A p. 28, No. 4 pp. 504-512, July 1980.

University of California, Berkeley — Electronic Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: EM-81-2(terminating in part) — Last Year's No.(s): EM-80-2

Title: Infrared and Optical Antennas and Guides

Senior Principal Investigator(s):	D. J. Angelakos	(415) 642-7200
	K. K. Mei	2-4106
	S. E. Schwarz	2-5684

Scientific Objective

Antennas and guides in the infrared and optical region of the electromagnetic spectrum are expected to have applications for radiation detection, astronomy, communications, and other fields. For example, it has been shown that the use of antennas can provide order-of-magnitude improvements in infrared detector performance [9]. Antenna-coupled devices have also been used to obtain accurate frequency measurements at frequencies as high as the visible, and to obtain a measurement of the speed of light 100 times more accurate than those preceeding [11].

The analysis and design of infrared antennas involves certain problems which are different from traditional work on lower-frequency antennas. Some of these differences are as follows: (a) The electric properties of metals are altered at high frequencies; (b) Typical antenna dimensions are comparable to wavelength, hence for optical antennas novel antenna designs are required to accomodate available microfabrication techniques; (c) correspondingly, because of the extreme smallness of optical wavelengths, antenna dimensions may at times be large compared with wavelength. Excluding reflector type antennas, this is a case not often encountered in traditional antenna research.

Guiding the signals at optical frequencies poses fundamental problems of electromagnetics, whether optical waveguides, strip-lines or other transmission systems are to be used. In the optical region the use of dielectric fiber waveguides in the realization of transmission systems has grown markedly. There are a great number of theoretical and practical electromagnetic problems that have not as yet been solved due to the complexity of the hybrid propagation modes in the fiber. The particular basic problems of coupling between guides and the scattering from obstacles, such as local impurities, are of fundamental importance with respect to the application of fibers to communication systems and the development of new devices.

State of the Art

Basic electromagnetic problems have appeared ever since infrared- and optical-frequency devices have been in existence. The two areas of concern in this proposal involve antennas and guides at these frequencies.

Infrared and Optical Antennas - It has been recognized for some time that metal-insulator-metal (MIM) "optical" diodes (also known as "MOM" or "MBM" diodes) can be coupled to the electromagnetic field by means of an antenna which is identical with the cat whisker of the diode [1]. Matarrese and Evenson have shown that the dependence of the output of a whisker diode on its orientation while illuminated by an infrared laser beam can be explained by considering the structure as a simple long-wire antenna [2]. They have published antenna patterns at 337μ. Professor Schwarz and his coworkers have obtained well-defined receiving-antenna patterns at wavelengths as short as 3μ, also by means of metal-whisker antennas [3]. Professor Wang has applied the theory of linear antennas to derive an expression for the optical voltage variation with frequency [4]. Planar evaporated type of antennas have been attempted but as yet have not met with complete success.

Infrared and Optical Guides - Until now optical waveguides have been primarily of the fiber type. The objective of this proposed study is to investigate the processes of mode conversion and radiation that come into play when an object of different dielectric constant is introduced into either the fiber or the fiber cladding. Investigations thus far have been restricted to the scattering from point inhomogeneities [5,6,7,8]. Such a treatment allows one to approximate the effects by using a modified Rayleigh approach which examines the current induced on the obstacle. Only the HE_{11} mode has been treated with any detail; the results are thus limited in usefulness. The proposed research would deal with the problem in a more general sense. The hybrid modes will be examined without reference to a specific mode. Also, the dimensions of the scatterer are not restricted to the Rayleigh region.

Other types of optical transmission lines such as those using metallic conductors or using portions of the substrates have not been sufficiently investigated and seem to offer substantial new possibilities. Here a good deal of basic research is required. Metallic conductors are comparatively lossy, but there are important applications, such as coupling together elements of antenna arrays, where only short distances are required. Metal-conductor guides have the virtue of closely confining energy, for easy coupling to diodes or antennas. Dielectric waveguides such as ridge waveguides are, on the other hand, promising for use in applications where longer distances of propagation are required.

Progress and Publications

Considerable progress was made in design and analysis of antennas suitable for us in millimeter-wave integrated circuits. Tapered-dielectric-waveguide antennas have been fabricated monolithically in silicon and tested at wavelengths of 1.3 and 0.119 milimiters. The results have appeared as an invited paper entitled, "Antennas and Waveguides for Far-Infrared Integrated Circuits," by D. B. Rutledge, S. E. Schwarz, T. L. Hwang, D. J. Angelakos, K. K. Mei and S. Yokota, IEEE Jour. Qant. Elect., vol. QE-16, pp. 508-516, May 1980. An abstract of this work follows:

> Antennas and waveguides for the wavelength range 0.1-3 mm are considered. Emphasis is placed on those designs which lend themselves to integration with each other and with other components such as diodes. The general properties of FIR antennas are reviewed. A novel silicon waveguide antenna is discussed, and its design, simulation, fabrication, and performance at 119μm are described. This antenna has a highly symmetrical, single-lobed beam with 3 dB beamwidths of 35 and 38° in the E- and H-planes, respectively. The gain (measured in microwave simulation) is 12.8 dB. This antenna is well-suited for integration with Schottky diodes.
>
> The related subject of FIR waveguides is discussed. Experiments with metal transmission lines at 119μm are described and dielectric guides related to the waveguide antenna are also considered. Using components such as these it may soon be possible to construct receiver front ends for this wavelength range in integrated circuit form.

Progress and Publications, cont'd

This work is continuing under other sponsorship. The principles devised earlier are now being applied to integrated antenna-diode mixer structures.

A different type of antenna was devised for use in multi-mode detector arrays. Arrays of 400 microbolometer detectors (array size, 1 cm^2) were designed and tested at 230 GHz. Theoretical analysis based on the EMF Method was in good agreement with experiment. These results are reported in "Planar Multi-Mode Detector Arrays for Infrared and Millimeter-Wave Applications," by D. B. Rutledge and S. E. Schwarz, to appear in IEEE Jour. Quant. Elect. Abstract of the paper is as follows:

> A new type of detector array is described. By means of a suitably designed metallic network, many detector elements (each individually small compared to wavelength) are assembled into an impedance-matched termination for radiation incident normally on the plane of the device. Residual reactance is tuned out by means of a movable backshort. An array of 400 bismuth-film microbolometers with a total area of one cm^2 has been tested at 215 GHz. A coupling efficiency of approximately 60% was observed. The detector has a D^* of 4×10^8 cm $Hz^{1/2}/W$ at room temperature with response time on the order of 2×10^{-7} second. Similar arrays of Schottky and SIS diodes can probably be constructed.

This work is not at the moment being continued but may be revived as required for progress toward major program objectives.

Both of the abovementioned publications acknowledged partial JSEP support.

During the reporting period, David B. Rutledge completed his doctoral thesis, entitled "Submillimeter Integrated Circuit Antennas and Detectors." Dr. Rutledge has now taken a position as Assistant Professor of Electrical Engineering at the California Institute of Technology. The abstract of Rutledge's dissertation is:

> Integrated-circuit techniques promise to make possible reliable submillimeter devices and arrays. This thesis discusses three different integrated-circuit antennas. The first is an evaporated V-antenna in a sandwich of crystal-quartz substrates. This was the first evaporated submillimeter antenna to have a predictable pattern, and it has been successfully tested in a plasma interferometer at 119 μm. The second is a dielectric-waveguide antenna, made by anisotropic etching of silicon. This antenna has been integrated with a Schottky diode. The final antenna is a multi-mode, tunable array of 400 microbolometers. This approach gives efficient coupling between a source and the detectors. The array achieves a D^* of 2×10^8 cm $Hz^{1/2}/W^{-1}$ at 1.4 mm with a modulation frequency of 1 MHz.

Significant Accomplishments

The novel structures devised in this reporting period have clear applications, both demonstrated and potential. The single-mode antennas are promising candidates for inclusion in developing millimeter-wave IC technology, and suggest avenues for progress in waveguides for this application. The multi-mode antenna structure has already been shown, when used with simple microbolometers, on FIR detector as sensitive as the common pyroelectric detectors and several orders of magnitude faster. This technique can be adapted to produce large-area detector arrays based on other kinds of small detectors, such as diodes or SIS junctions.

Contacts with Other Agencies

We have been in frequent contact with scientists of the U.S. Army Harry Diamond Laboratory, U.S. Army Research Office, and the U.S. Army Night Vision Laboratory at Fort Belvoir. Related work in our group is presently sponsored by ARO, and a proposal to NVL (involving practical applications of novel techniques developed under JSEP) is pending.

Other related work in our group is supported by the National Science Foundation. The latter organization conducts annual meetings on the subject of Optical Communications. These have often supplied useful motivations for research to be conducted under JSEP. We have also had useful contacts with scientists of the Aerospace Corporation.

References

[1] L. O. Hocker, D. R. Sokoloff, V. Danpu, A. Szoke, and A. Javan, Appl. Phys. Lett., 12, 401 (1968).

[2] L. M. Matarrese and K. M. Evenson, Appl. Phys. Lett., 17, 8 (1970).

[3] B-L. Twu and S. E. Schwarz, Appl. Phys. Lett., 26, No. 12, 672-675 (1975).

[4] S. Wang, Appl. Phys. Lett. 28, 303 (1976).

[5] G. L. Yip, "Launching Efficiency of the HE_{11} Surface Wave Mode on a Dielectric Rod," IEEE Trans. on Microwave Theory Tech., Vol. MTT-18, No. 12, pp. 1033-1041 (1970)

[6] A. W. Snyder, "Excitation and Scattering of Modes on a Dielectric or Optical Fiber," IEEE Trans. on Microwave Theory Tech., Vol. MTT-17, No. 12, pp. 1138-1144 (1969).

[7] P. J. B. Clarricoats and K. B. Chan, "Propagation Behaviour of Cylindrical-Dielectric-Rod Waveguides," Proc. Inst. Elec. Eng. (London), Vol. 120, No. 11, pp. 1371-1378.

[8] G. L. Yip and J. Martucci, "Scattering From a Localized Inhomogeneity in a Cladded Fiber Optical Waveguide. 1: Radiation Loss," Applied Optics, Vol. 15, No. 9, pp. 2131-2136 (1976).

References, concluded

[9] S. E. Schwarz and B. T. Ulrich, J.A.P., Vol. 48, 5, pp. 1870-1873 (1977.)

[10] T-L. Hwang and S. E. Schwarz, Appl. Phys. Lett., 31, No. 2, pp. 101-104, (1977).

[11] K. M. Evenson, J. S. Wells, F. R. Petersen, B. L. Danielson, G. W. Day, R. L. Barger, and J. L. Hall, Phys. Rev. Lett., 29, p. 1346 (1972).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

II.A. Basic Research in Solid State Electronics - Materials — Coordinator: Professor S. Wang

General

The main objectives of the proposed research program are: (1) to characterize the carrier lifetime profiles and the deep levels in ion implanted semiconductors for an understanding of the lifetime degradation mechanism, gathering information for advance device design, and search for improved technologies, and (2) to explore the use and study the properties of ternary and quaternary III-V compounds for advanced and improved electronic devices and to develop the necessary growth and processing technologies for these compounds. The goal of the second objective is to find an optimal approach to and to develop the MBE and LPE technology for integrating electronic and optical devices for fast communication and signal processing.

Ion implantation is a technology of great promise for its ability to dope a semiconductor with precise control of the doping profile. Among the properties of the ion-implanted semiconductors, the least known and understood is the carrier recombination lifetime. The lifetimes within the implanted layers have not been quantitatively measured (leaking current of an implanted diode mostly reflects the lifetime of the substrate). We propose to measure the lifetime profiles with sub-micron resolution using a novel technique, which also determines the built-in electric field profile. For a basic understanding of the lifetime degradation, we propose to correlate the lifetime profiles with the densities of deep levels measured by transient C-V measurements. Using these characterization techniques as tools we plan to search for the optimal annealing cycle, to examine the effects of laser annealing, and to develop a novel technique of eliminating the defect-causing stress in implanted semiconductors by co-implanting two dopants of different atomic sizes.

One important area of materials research is III-V compounds on account of their unique properties for a wide range of device applications, such as lasers, photodetectors, Gunn-effect devices, and field-effect transistors. One fruitful area of research is to examine the unique possibility of combining various III-V compound electronic and optical devices for communication and signal processing and to develop the needed technical capability for fabricating integrated opto-electronic circuits. In our laboratory, we have accumulated extensive knowledge and experience on the (GaAℓ)As system from our work on GaAs-(GaAℓ)As lasers. So far, we have used the LPE process to fabricate the basic structures for opto-electronic integration. However, the LPE technology has its limitations in precise control of film thickness and doping profiles. We propose that we study and develop the MBE technology as a means of fabricating optical and electronic devices. Besides high electron mobility and direct-gap band structure, another advantage of III-V compounds is that the compounds are miscible so that the material parameters can be optimized in a given application. The (GaIn)(AsP) quarternary system is especially interesting for being possible to get perfect lattice match to the InP substrate. We further propose that our LPE work be extended to the (GaIn)(AsP) quarternary system. Liquid-phase-epitaxy growth conditions will be studied to control the amount of lattice mismatch

and experiments will be performed to examine the junction properties sensitive to interface defects, such as the surface recombination velocity and interface state density at the heterojunction, and to correlate the measured properties with the degree of lattice mismatch. We believe that such studies will contribute to our fundamental understanding of semiconductor heterojunctions. Lattice defects such as dislocation lines terminating at the heterojunction affect bulk as well as interface properties. Lifetime and quantum efficiency in the (GaIn) (AsP) LPE grown layers will be measured, and thermal expansion coefficients of the quaternary compound will be determined. The proposed research program is designed to study the effects and causes of defects introduced by lattice mismatch so that a basic picture of semiconductor heterojunctions may emerge. An integral part of the research program is the development of suitable technologies for processing the quaternary compound, needed for device fabrication and surface passivation. Experiments such as chemical etching and anodic oxidation in which we have done extensive work for the GaAs-(GaAl)As system will be extended to the InP-(GaIn)(AsP) system.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSM-81-1 (terminating) — Last Year's No.(s): SSM-80-1

Title: Lifetime Studies in Ion-Implanted Semiconductors

Senior Principal Investigator(s): C. Hu (415) 642-3393
W. G. Oldham 2-2318

Scientific Objective

In order to characterize the ion-implanted semiconductors, we shall develop a novel technique of measuring the carrier lifetime profile with submicron resolution and the interface recombination velocity, in the presence of arbitrary and unknown electric field. The lifetime profile will be compared with the density distributions, energies, and cross sections of the deep levels that may exist. Using these characterization techniques, we shall explore the possibilities of improving the lifetimes by optimizing the annealing cycle, laser annealing, or a novel method of eliminating the stress in heavily implanted semiconductors.

State of the Art

The impact of ion implantation on the semiconductor technology has been strong and broad and is expected to deepen even more rigorously. Basic understanding of some of the ion implantation phenomena has not kept pace with the expanding applications. In particular, the recombination lifetimes within the ion implanted layers have not been studied with any accuracy. Neither have the recombination levels responsible for the lifetime degradation been characterized.

It is known that large numbers of lattice defects are created by ion implantation as the energy of the ion is dissipated by displacing the host atoms from their regular lattice sites. The density and distributions have been studied[1,2]. The area density of lattice disorder measured by ion scattering[3] increases with the implantation doses linearly until the top surface layer becomes amorphous. Each implanted ion can create several thousand lattice defects[4] when the implantation is performed at room temperature.

Annealing can reduce the number of lattice defects, but typically some of the disorder remains even after high temperature (900°C) annealing[3]. Remnant lattice defects can have significant effects on the electronic properties of the material. Lattice damage is directly and indirectly responsible for the degradation of carrier lifetime in ion implanted materials. Lifetime in silicon damaged by low doses of implanted ions may be restored by annealing at 900°C. At higher doses, some degradation remains even after 1000°C anneal[5,6]. Since the defects may be electrically active, the carrier density is influenced by the defect density. In fact, even change of conductivity type (p or n type) during annealing is not uncommon[7]. In some semiconductors the compensation is such that the carrier concentration does not vary with the implantation[8].

Most of the lifetime studies performed to date measured the reverse leakage current of ion implanted pn diodes[8-10] or the generation current in the MOS diodes[11]. However, the generation lifetime cannot be equated with the recombination lifetime. Besides, the junction leakage current does not yield reliable information about the lifetime in the implanted layer. The leakage current is determined by the lifetime in the space charge depletion layer, which lies almost entirely in the unimplanted substrate. The damage in the implanted layer could actually improve the lifetimes in the depletion region by gettering the lifetime killers[10]. Generation lifetime longer than 200 μs has been measured[12].

To our knowledge, only one group has attempted to study the lifetimes within the ion implanted layers[13,14]. The diodes used were phosphorus diffued planar diodes on 5Ω-cm p type substrates. The junctions were about 1 μm deep. To generate damage beneath the junction, 1.5 MeV silicon ions and 2 MeV carbon ions were implanted. The ion range was estimated to be 1.4 μm. Even that study had the same serious drawback. Assuming a 0.1 μs lifetime, the diffusion length is about 20 μm. This means that most of the injected carriers are stored in the undamaged material outside the sub-micron damaged region. The measured lifetime is probably not characteristic of the ion-implanted layer. Watanabe et al.[15] recently demonstrated that the lifetime in an ion-implanted Si sample might vary over several orders of magnitude over a sub-micron distance. What is needed is a technique to quantitatively measure the lifetime with a resolution much better than a diffusion length.

Naturally, the lifetimes in the implanted layers have not been correlated with the deep energy levels that may be present. Kimerling[16] has determined the deep energy levels introduced by proton implantation by a junction capacitance technique. These results may not apply to samples implanted with other ions such as boron and phosphorus, for many defects are associated with the implanted impurities[17]. Schulz[18] has used ion implantation as a tool to study the deep levels introduced by various implanted impurities in silicon. His method of determining the density and energy of deep levels is relatively simple. However, it can not determine the spatial distribution of the deep levels.

Progress and Publications Since Last Major Proposal

All publications reported in this section were results of JSEP supported research.

We have proposed and analyzed a unique technique that can measure the nonuniform diffusion length L(x) in the presence of an unknown electric field $E_x(x)$ with a sub-micron resolution. This technique is well suited to the study of ion-implanted layers, which have spatially varying lifetimes and, usually, high built-in electric field. Previously, diffusion length or lifetime could not be measured with better resolution than a diffusion length. The principle of the technique has been published [C. Hu, "Determination of Nonuniform Diffusion Length and Electric Field in Semiconductors," IEEE Trans. Elec. Dev, ED-25, 822-825, 1978]. Fig. 1a shows one of the possible test configurations. The region of interest is sandwiched by two reverse biased p-n or Schottky junctions at x = 0 and x = w. The y = 0 plane is a cleaved surface, perhaps passivated with a thin oxide layer. The electron beam scans from $x_s = 0$ to $x_s = w$. The diffusion length, and the electric field can be obtained from the measured currents $I_o(x_s)$ and $I_w(x_s)$.

$$L(x_s)^{-2} = (I_w'I_o'' - I_o'I_w'')/(I_oI_w' - I_xI_o')$$

$$E_x(x_s) = \frac{kt}{q}\{\ln[I_o^2(I_w/I_o)']\}$$

Primes and double primes indicate the first and second derivatives with respect to x_s. One may appreciate the novelty of the results more when considering that there are no analytic solutions to the reverse problem, i.e. there are no analytic solutions for $I_o(x_s)$ and $I_w(x_s)$ when L(x) and E(x) are general known functions.

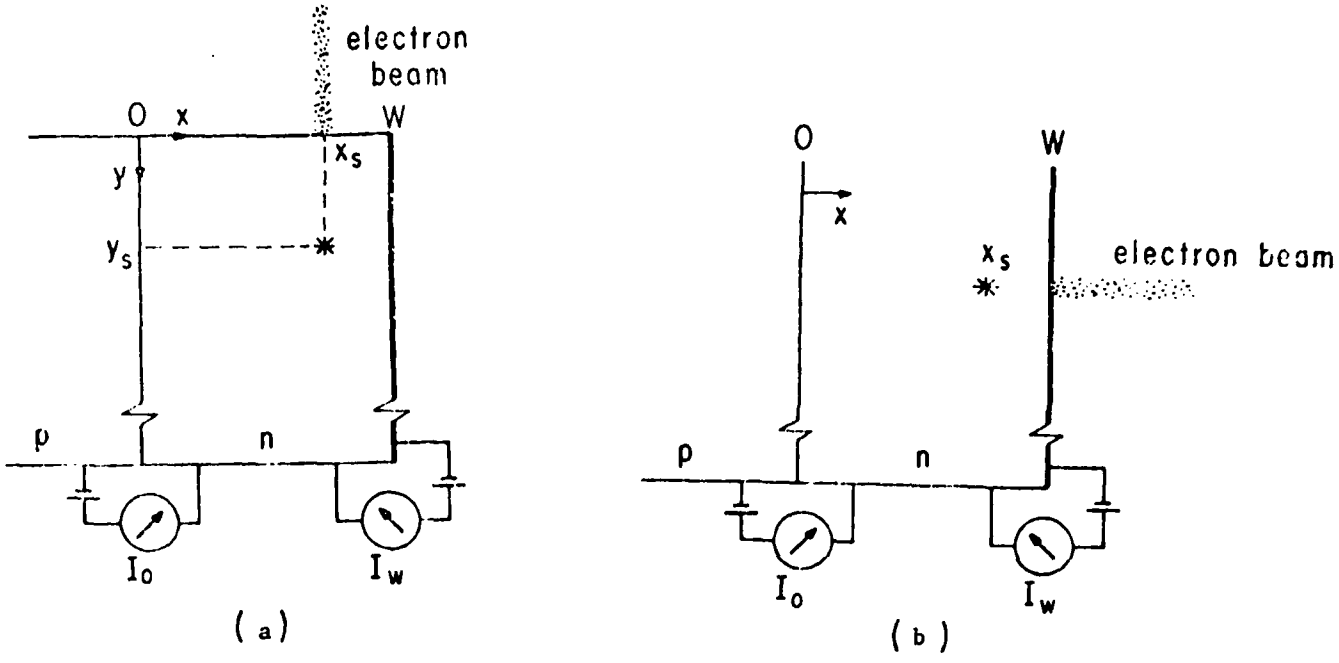


Fig. 1

A Ph.D. student, Clifford Drowley has carried out the experiment. He has fabricated samples in the form of Fig. 1a. Results indicated that surface recombination at the y = 0 plane complicates the interpretation of the data. Another Ph.D. student, Min-hwa Chi, is using the configuration shown in Fig. 1b, where x_s is varied by changing the electron beam voltage. In that case, the electron generated is not confined to a single x_s as shown by Everhart of this laboratory and the induced current must be convoluted with the carrier generation function. Results so far are encouraging.

Meanwhile, we have extended the theory of the method to include ac electron beam excitation. The beam induced currents would contain both magnitude and phase information. This expectedly further broadens the method's capability. $\tau(x_s$ and $D(\tau_s)$ may be independently measured and only one junction is needed, not two. We have succeeded in obtaining a $5,820 grant from the University and ordered a Princeton Applied Research Model 5021 50 MHz lock-in

amplifier to implement this improved technique.

Mr. Drowley has also been studying methods of annealing ion-implanted Si. He has successfully demonstrated annealing by focused light from a high intensity Xenon arc lamp. This may be an alternative to furnace annealing and laser annealing. Small samples as As-implanted ⟨100⟩ Si (10^{16} ions/cm^2, 200 keV, resulting in an amorphous surface) have been recrystalized. Steady state temperatures greater than 1090° C have been attained; recrystallization is quite rapid at these temperatures and occurs within 10 seconds at 700° C. TEM investigations have verified the recrystallization of the amorphous layers, and the regrown layers exibit 6 - 10 times smaller sheet resistivity than unannealed samples. A publication on this study is being prepared.

Mr. Chi has set up the transient C-V spectroscopy[19-21] experiment for profiling the trap densities and the energy, as well as spatial distributions. In the course of this work, we have recognized that the low speed of capacitance measurement and the resulting need for sample cooling is a major drawback of this technique. As a result, we have investigated a recently proposed method, transient V_g spectroscopy that achieves the same end by monitoring the transient change in the threshold voltage of a MOSFET after a step change in the substrate bias[29]. A paper entitled, "Errors in Threshold Voltage Measurements of MOSFET for Dopant Profile Determination" has been accepted for publication by Solid State Electronics. This new technique has been demonstrated in our laboratory.

Ion-implanted semiconductors are often heavily doped. We have studied the degradation of lifetime in bulk heavily doped silicon. This degradation is generally attributed to Auger recombination. This attribution has never been unambiguously proved. We theoretically examined an alternative mechanism - recombination through neutral donors or acceptors. Somewhat surprisingly, this mechanism could explain the $\tau \propto 1/n^2$ relationship, the weak temperature dependence of τ and the deduced neutral trap capture cross-section is consistent with the value measured at low temperatures. This and the Auger mechanisms can be distinguished by studying heavily compensated semiconductors. This work is reported in C. Hu and W. G. Oldham, Appl. Phys. Lett., pp. 636-639, Oct. 15, 1979, an abstract of which follows:

> Carrier recombination in heavily doped semiconductors via shallow donor or acceptor states is analyzed. The results are in general agreement with experimental lifetime observations including the $1/n_o^2$ or $1/p_o^2$ dependence, and the insensitivity to temperature and to the dopant used. Capture cross sections of about 10^{-20} cm^2 needed to fit the lifetime data are reasonable for neutral traps and are consistent with low-temperature capture cross sections reported for shallow dopants.

Significant Accomplishments

We have implemented and improved a new deep level transient spectroscopy technique that uses MOSFET structure and does not require capacitance measurement. It is a simpler technique and is capable of measuring microsecond transients easily. We have demonstrated the annealing of ion-implanted Si,

Significant Accomplishments, cont'd.

using focused light from a CW arc-lamp. Compared to a laser, an arc-lamp is not only much cheaper but also has 300 times higher energy efficiency. the wide band spectrum also minimizes the interference effects of SiO_2 overlayers. We have pointed out recombination through neutral donors as a possible explanation for the degradation of lifetime in heavily doped silicon.

Interaction with Other Work Units

The characterization techniques to be developed under this project will be quite useful to the "III-V Semiconductor Materials" project (SSM-81-2). Results regarding the lifetimes in ion-implanted material and improved technologies will be helpful to all IC technology, devices and circuits research.

References

[1] D. K. Brice, Ion Implantation, Plenum, 1973, p. 171

[2] E. Bogeh, P. Stensgaard, 1970 Proc. of 1st Int. Conf. on Ion Implantation, p. 431

[3] J. W. Meyer, L. Eriksson, J. A. Davis, Ion Implantation in Semiconductors, Academic Press, 1970.

[4] D. A. Marsden, et al., Phys. Status Solidi, 35, 269, 1969.

[5] R. W. Bicknell, R. M. Allen, Ion Implantation, p. 63, Gordon and Brach, 1971.

[6] A. E. Michel, F. F. Fand and E. S. Pan, J. Appl. Phys., 45, p. 2991, 1974.

[7] N. G. E. Johannsson, Solid State Elec., 13, 123, 1970.

[8] L. Palmelshoefer, et al., Appl. Phys. Lett., 11, 559, 1977.

[9] B. A. MacIver, E. Greenstein, J. Electrochem. Soc., 124, p. 273, 1977.

[10] E. H. Bogardus, J. Appl. Phys., 48, p. 2093, 1977.

[11] Y. Wada, M. Ashikawa, Japan J. Appl. Phys., p. 1045, Sept. 1975.

[12] K. A. Pickar, et al., Appl. Phys. Lett., 19, p. 43, 1971.

[13] D. Eirng Davies, S. A. Roosild, Appl. Phys. Lett., 17, p. 107, 1970.

[14] D. Eirng Davies, S. A. Roosild, Solid State Elect., 14, p. 975, 1971

[15] M. Watanabe, G. Actor, H. C. Gatos, IEEE Trans. Elec. Dev., ED-24, p. 1172, 1977

References, concluded

[16]L. C. Kimerling, Inst. of Phys. Ser. No. 23, 1975, Ch. 1. and J. Appl. Phys., 45, p. 1839, 1974.

[17]R. W. Beezhold, K. L. Brower, IEEE Trans. Nuc. Sci., NS-19, p. 209, 1973.

[18]M. Schulz, Appl. Phys., 3, 1974, and Inst. of Phys. Serv. No. 22, 226, 1974.

[19]C. T. Sah, IEEE Trans. Elec. Dev., p. 410, April 1977.

[20]D. V. Lang, J. Appl. Phys., 45, p. 3023, 1974.

[21]G. L. Miller, D. V. Lang, L. C. Kimerling, Ann. Rev. Mater. Sci., 377-448, 1977.

[22]E. P. Eernisse, Appl. Phys. Lett., 18, 581, 1971.

[23]K. Seshan, Appl. Phys. Lett., 33, 21, 1978.

[24]T. H. Yeh, M. L. Joshi, J. Electrochem. Soc., 1, 74, 1969.

[25]Y. T. Lee, et al., J. Electrochem. Soc., 4, 530, 1975.

[26]R. T. Young, C. W. White, G. J. Clark et al., Appl. Phys. Lett., 32, 139, 1978.

[27]A. Gat, J. F. Gibbons et al., Appl. Phys. Lett., 32, 276, 1978.

[28]B. C. Larson, C. W. White, B. R. Appleton, Appl. Phys. Lett., 32, 801, 1978.

[29]L. Forbes, R. Brown, M. Sheikholeslam, Solid State Elec., 22, 391, 1979.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSM-81-2 — Last Year's No.(s): SSM-80-2

Title: Compound Semiconductors: Material-Property and Device Studies

Senior Principal Investigators(s): C. Hu (415) 642-3393
S. Wang 2-4134

Scientific Objective

We propose to study the properties of the quaternary compound (GaIn)(AsP) and the ternary compound $Ga_{0.47}In_{0.53}As$ concerning LPE growth, lasing characteristics, ohmic-contact formation, and Schottky-barrier height. The quaternary compound is important for its spectral coverage best suited for fiber optical communications, and will be studied as laser material. The ternary compound is promising for its theoretically predicted high mobility and peak drift velocity. Our objectives are to find the dominant factors affecting LPE growth, lattice mismatch, impurity concentration, contact resistance and Schottky-barrier height in these materials, and to correlate the material properties, such as lattice mismatch, doping profile and material-composition profile, with the device performance, such as lasing characteristics, turn-on voltage, and I-V characteristics, and with the electrical measurements, such as carrier concentration and mobility.

State of the Art

III-V compound semiconductors possess many distinct and unique advantages as an electronic and optical material. Most of the compounds of smaller gap energy, such as InAs and InSb, have very small electron mass and thus exceedingly high electron mobility. Some of the compounds of larger gap energy, such as InP and GaAs, can be made semi-insulating by compensation either through deep donors or through deep acceptors. The compounds are almost completely miscible except in some systems where a small miscibility gap exists. The mixed compounds can be lattice-matched to a given substrate, for example $(Ga_{1-x}In_x)(As_{1-y}P_y)$ to InP, by properly choosing the relative composition signified by x and y. The miscibility and the possibility of lattice-match of these compounds enable us to build electronic and optical devices with materials different from the substrate and thus to take full advantage of the material properties, for example (GaIn)As on InP, with the former for its high mobility and the latter for its semi-insulating property.

Most of the compounds are direct-gap semiconductors and hence attractive candidates as materials for lasers and photodetectors. In compounds where the energy gap is direct, the energy separation between the central valley (the direct gap) and the satellite valleys (above the central valley) of the conduction band varies from compound to compound. This variation offers various possibilities for mixed compounds. For mixed compounds with relatively small separation, for example 0.36 ev in GaAs, we expect the material to exhibit the so-called transferred-electron or Gunn effect. For mixed compounds with relatively large separation, we expect that the material should be able to attain a much higher drift velocity than the value limited by the transferred-electron effect. The possibility of a high-drift velocity makes these materials attractive candidates for FET. In any case, on a time scale shorter than the intervalley-scattering time, the electron drift-velocity is expected to continue to grow with increasing applied field to values beyond those limited by the transferred-electron effect. This

phenomenon, called velocity overshoot, makes compound semiconductors extremely attractive for ultra-high frequency applications.

Among III-V compounds, the GaAs/(GaAl)As system has been most extensively studied for both laser[1] and FET[2] applications. For the laser, a great deal of attention has been focused on stabilizing the mode by incorporating a two-dimensional waveguide in the structure, and remarkable progress has been made on the GaAs/(GaAl)As laser. Many lasers exhibiting linear light-versus-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser[3,4], the channeled-substrate-planar (CSP) laser[5,6], and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction[7-10]. Among the lasers referenced here are the IRW laser[7], the CJSF laser[7] and the narrow DCC-CSP laser[6] being developed and studied in our laboratory. Recently, the research interest has shifted from the GaAs/(GaAl)As laser toward the quaternary (GaIn)(AsP)/InP laser which covers the spectral range where optical fibers have exhibited minimum loss (around 1.55 micrometers) or zero dispersion (around 1.3 micrometers). Because the development of the quaternary laser is relatively recent, many problems including mode stability and temperature sensitivity have not been fully investigated and are yet to be overcome.

For the field-effect transistor, the emphasis is on low power and high speed, and a power/speed product around 20 fJ and a propagation delay around 100 ps have been reported by several laboratories (see papers appearing in the special issue of MTT, Reference 2). To further advance the FET technology, several important problems need to be overcome and have received prominent attention. One of the steps used in the fabrication of the FET is ion implantation. It is found, however, that considerable degradation of the doping profile takes place during annealing of Cr and S implants[11-13]. Although anodic oxidation has been tried on compound semiconductors[14], the interface-state density is considerably higher than that at Si/SiO_2 interface. For lack of a suitable insulator, most FET's are made of Schottky-barrier gates in the form of MESFET. However, the barrier height formed on Si and GaAs is generally not as high as we hope to have. Theoretical studies[15,16] have shown that the degree to which the barrier height at a metal-semiconductor interface is influenced by the metal work function is strongly dependent on the ionicity of the semiconductor. Because Si and GaAs are covalent the barrier height in these two materials is not expected to change much with the metal, as confirmed by experimental data[15]. Therefore, an interface material, such as silicide for silicon, must be found for compound semiconductors between the metal and the semiconductor.

Recently, the ternary compound $In_{0.53}Ga_{0.47}As$ has generated considerable interest, not only as a photodetector for the quaternary (GaIn)(AsP) laser, but also as a FET[17]. Theoretical calculations[18] of the low-field mobility and the peak drift velocity in the ternary compound show that mu = 9700 $cm^2/v\text{-}s$ and $v_m = 2.8 \times 10^7$ cm/s are higher than the corresponding values in GaAs and InP, even with alloy

scattering being taken into account. The quaternary (GaIn)(AsP) and the ternary $In_{0.53}Ga_{0.47}As$ compounds offer exciting research opportunities for their outstanding properties and for their relatively unexplored status. Our research efforts will be concentrated at first on those aspects for which we have acquired expertise and then extended to areas which, we think, are important and in which we can make significant contributions.

Progress and Publications

We started our work on LPE growth of InP films on Inp substrates and fabrication of InP p-n diodes about one and one-half years ago as a M.S. thesis project. During the initial phase, three problems were encountered: (1) thermal damage of the InP substrate, (2) large turn-on voltage (greater than 2 v) and (3) high contact resistance. The work is described in the M.S. thesis of K. D. Pedrotti, "Liquid Phase Epitaxial Growth of Indium Phosphide for Device Applications," Department of Electrical Engineering and Computer Science, University of California, Berkeley, December 1979. Since then these problems have been overcome, and a Ph.D. student started the work on LPE growth of the quaternary (GaIn)(AsP) films on InP substrates about eight months ago. Using a graphite cover plate, we have reduced thermal damage to an insignificant degree and thus been able to grow the first InP film as well as subsequent quaternary films of excellent quality when examined under the Nomarski interference microscope. Using evaporated and sintered Au/Zn film as the p-side contact, turn-on voltage around 1.4 v and contact resistance about 8 ohms for a 15 micrometer x 300 micrometer stripe-geometry laser are obtained. The contact resistance can be further reduced by Zn diffusion. This process will be tried soon. We are happy to report that even without Zn diffusion, we have been able to achieve lasing action in a majority of the stripe-geometry lasers tested. The lasers have a surprisingly small threshold current as low as 180 mA and show stable far-field radiation pattern in the fundamental transverse mode. The lasers also have a surprisingly small number of longitudinal modes which are centered around 1.248 micrometers. We are very pleased with the progress we have made during a relatively short period of time.

Besides the quaternary compound, we also made significant progress on GaAs-related work. Another M.S. student, Y-S. Kim, has developed a novel, simple method of measuring diffusion length and surface recombination velocity using a pn junction structure such as a solar cell. Chopped light that may be broadband is incident from the bulk site of the test cell. The photocurrent, I, is measured as a function of the effective bulk thickness of the cell, W, which is varied by varying the junction reverse bias. The diffusion length, L, and the surface recombination velocity of the bulk material can be deduced from the data without curve fitting. For example, $L^2 = Id^2(1/I)d^2W$. This work has been reported (Y. S. Kim, C. Hu and C. Drowley, Record 14th Photovoltaic Specialist Conference, pp. 596-600, Jan. 1980).

In support of the development of III-V compound power devices, a comprehensive analysis of power MOSFET's was made and presented (C. Hu,

"Parametric Study of Power MOSFET's," 1979 IEEE Power Electronics Specialists Conference, San Diego, June 1979, pp. 385-395.) It was shown that the bulk ohmic drop is the principal contributor to the on-state voltage -- a conclusion favorable to GaAs high electron mobility. Furthermore, using the technique of variational calculus, we have derived the optimum doping profile that minimizes the ohmic resistance while maintaining a required breakdown voltage. The minimized resistance is proportional to the 2.5th power of the breakdown voltage. This work appeared in IEEE Trans. on Elec. Dev., vol. ED-6, 243, March 1979.

Interaction With Other Work Units

Close interaction is expected with the work units on MBE and on ion-implanted semiconductors, and frequent consultation is also anticipated with other work units, mainly in the IC and device area, for electrical measurements.

References

(1) See, for example, M. C. Casey, Jr., and M. B. Panish, Heterostructure Lasers, Academic Press, (1978); H. Kressell and J. K. Butler, Semiconductor Lasers and Heterojunction LED's, Academic Press (1947).

(2) See, for example, C. A. Liechti, "Microwave field-effect transistors - 1976," IEEE Trans. Microwave Theory and Techniques, vol. MTT-24, pp. 279-300 (1976); R. L. van Tuyl et al., "GaAs MESFET logic with 4 GHz clock rate," IEEE J. Solid-State Circuits, vol. SC-14, pp. 486-496; R. C. Eden et al., "The prospects for ultrahigh-speed VLSI GaAs digital logic," IEEE J. Solid-State Circuits, vol. SC-14, pp. 221-239 (1979); C. A. Liechti, "GaAs FET technology: A look into the future," Microwaves, pp. 44-49, October (1979); and papers in Special Issue on Gigabit for Microwave Systems, IEEE Trans. Microwave Theory and Techniques, vol. MTT-28, pp. 442-486 (1980).

(3) T. Tsukada, "GaAs-$Ga_{1-x}Al_xAs$ buried-heterostructure injection lasers," J. Appl. Physics, vol. 45, pp. 4899-4906 (1974).

(4) W. T. Tsang, R. A. Logan and M. Ilegems, "High-power fundamental-transverse-mode stripe buried heterostructure lasers with linear light-current characteristics," Appl. Phys. Lett., vol. 32, pp. 311-314 (1978).

(5) K. Aiki, M. Nakamura, T. Kuroda, J. Umeda, R. Ito, N. Chinone, and M. Maeda, "Transverse mode stabilized AlGaAs injection laser with channeled-substrate planar structure," IEEE J. Quantum Electron., vol QE-14, pp. 89-94 (1978).

(6) C. Y. Chen and S. Wang, "Narrow double-current-confinement channeled-substrate-planar laser fabricated by double-etching technique," Appl. Phys. Lett., vol. 36, pp. 634-636 (1980).

(7) L. Figueroa and S. Wang, "Inverted-ridge-waveguide double heterostructure laser with current and lateral optical confinement," Appl. Phys. Lett., vol. 31, pp. 122-124 (1977); "Curved-junction stabilized filament (CJSF) double heterostructure injection lasers,"

Appl. Phys. Lett., vol. 32, pp. 85-87 (1978).

(8) R. D. Burnham, D. R. Scifres, W. Streifer, and E. Peled, "Nonplanar large optical cavity GaAs/GaAlAs semiconductor laser," Appl. Phys.Lett., vol. 35, pp. 734-736 (1979).

(9) T. Sugino, K. Itoh, M. Wada, H. Shimizu, and I. Teramoto, "Fundamental transverse and longitudinal mode oscillation in terraced substrate GaAs/(GaAl)As lasers," IEEE J. Quantum Electron., vol. QE-15, pp. 714-718 (1979).

(10) T. Furuse, I. Sakuma, Y. Ide, N. Nishida, and F. Saito, "Transverse mode stabilized AlGaAs DH laser having a built-in plano-convex waveguide," paper 2.2, Proc. Optical Communication Conference, Amsterdam Sept. 17-19 (1980).

(11) P. K. Vasudeo and R. G. Wilson, "Damage gettering of Cr during annealing of Cr and S implants in semiconducting GaAs," Appl. Phys. Lett., vol. 37, pp. 308-310 (1980).

(12) T. Tsuji and H. Hasegawa, "Degradation of the doping profile of epitaxial GaAs layers due to an ion implantation process," Electron Dev. Lett., vol. EDL-1, pp. 112-113 (1980).

(13) P. M. Asbeck, J. Tandon, B. M. Welch, C. A. Evans, Jr., and V. R. Deline, "Effects of Cr redistribution on electrical characteristics of ion-implanted semi-insulating GaAs," Electron Dev. Lett., vol. EDL-1, pp. 35-37 (1980).

(14) H. D. Law, "Anodic oxidation of InGaAsP," Appl. Phys. Lett., vol. 37, pp. 68-70 (1980).

(15) S. Kurtin, T. C. McGill and C. A. Mead, "Fundamental transition in the electronic nature of solids," Phys. Rev. Lett, vol. 22, pp. 1433-1436 (1969).

(16) S. G. Louie, J. R. Chelikowsky and M. L. Cohen, "Ionicity and the theory of Schottky barriers," Phys. Rev. B., vol. 15, pp. 2154-2162 (1977).

(17) R. F. Leheny, R. E. Nahory, M. A. Pollack, A. A. Ballman, E. D. Beebe, J. C. Dewinters, and R. J. Martin, "An $In_{0.53}Ga_{0.47}As$ junction field transistor," Electron Device Lett., vol. EDL-1, pp. 110-111 (1980).

(18) M. A. Littlejohn, R. J. Hauser, T. H. Glisson, D. K. Berry, and J. W. Harrison, "Alloy scattering and high field transport in ternary and quaternary III-V semiconductors," Solid State Electron., vol. 21, pp. 107-115 (1978).

(19) D. C. Mayer, N. A. Masnari, and R.J. Lomax, "A vertical-junction field effect transistor," IEEE Trans. Electron. Devices, Vol. ED-27, pp. 956-961 (1980).

(20) K. Asai, Y. Ishi, and K. Kurumada, "P-column gate FET," Electron Device Lett., Vol. EDL-1, pp. 83-85 (1980).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSM-81-Suppl. (1) — Last Year's No.(s): None

Title: Molecular Beam Epitaxy and Its Application to Studies of Materials Aspects of Microstructure Engineering

Senior Principal Investigator(s): S. Wang (415) 642-4134
C. Hu 2-3393

Scientific Objective

Recent advances in thin-film growth technology have opened exciting opportunities, not only in the development of new device structures, but also in our quest for a better understanding of material properties. The objectives of this research program are (1) to master the MBE growth technology for III-V compound semiconductors and to develop the associated processing techniques, such as etching and masking, suitable for the MBE process, and (2) to analyze, to characterize, and to correlate the properties of the materials grown under different growth conditions. Our goals are to seek an optimal approach and to develop the needed technology for fabrication of devices of micron and submicron dimensions where interface and surface properties are expected to play a crucial role.

State of the Art

Over the last several years, significant progress has been made in the thin-film technology based on epitaxy for the fabrication of optical and microwave semiconductor devices. The three basic methods are liquid-phase epitaxy[1] (LPE), vapor-phase epitaxy[2] (VPE), including metal organic chemical vapor deposition[2] (MO-CVD, a form of VPE), and molecular beam epitaxy[3] (MBE). Among the three, LPE is the most extensively used, especially in the fabrication of double-heterostructure (DH) injection lasers. While the LPE technology has some distinct advantages over the VPE and MBE technology, it has its limitations. One obvious disadvantage is the lack of control on the film thickness and the impurity profile due to the fast growth rate. Another serious drawback is the impossibility of monitoring film growth and having the growth process temporarily stopped for analytical examination of the grown film. The MBE technology provides the answer to these problems and seems well suited as a research tool for the fabrication and study of semiconductor devices of micron and submicron dimensions.

One problem for which we must find a solution if we are to improve the quality of epitaxially grown films of compound semiconductors is the incorporation of unwanted impurities during the growth process. For example, a dominant shallow donor[4] was found in LPE-grown (GaAl)As and this impurity was thought to be sulphur introduced into the melt with aluminum. Contaminants[5] such as transition metals were reported to be present in MBE-grown GaAs. The total contamination incorporated in a MBE-grown film may be written as

$$C = (\xi/r_g)\ (d^2N/dt\ ds) \qquad (1)$$

where C is the impurity concentration, ξ is the sticking coefficient, r_g is the growth rate, and $d^2N/dt\ ds$ is the number of contaminant gas molecules striking the growth surface per cm^2 per sec. From kinetic theory of gases,

$$d^2N/dt\,ds = 3.5 \times 10^{22} P/(MT)^{1/2} \qquad (2)$$

where P is the partial pressure, M is the molecular weight, and T is the background gas temperature. Take CO as an example which has M = 28 AMU. At a typical growth rate r/dg/u = 1 μm/hr, the product ξ must be smaller than 7×10^{-15} in order to ensure $C < 10^{14}$ cm^{-3}. This simple calculation tells us that we must be extremely careful with contaminants with high sticking coefficients and high vapor pressure. It is important, therefore, for us to have analytical equipment, such as CMA and SIMS, to perform chemical analysis of the grown film and to use electrical measurements, such as transient capacitance-voltage spectroscopy, to characterize the incorporated impurities.

Progress and Publications

Under JSEP

This proposal was approved recently as a supplementary proposal submitted last year, and laboratory work commenced only after the arrival of the MBE system in June of 1980. In preparing for work proposed here, we have done extensive literature surveying to get familiarized with the MBE growth process and to know the relative merits, as well as limitations, of the MBE, LPE, and VPE processes. Before deciding on the specifics of the MBE system we would like to have, we talked with resarchers in the field and arranged several visits to laboratories to see demonstrations of the MBE growth process. Finally we decided on the Riber Model 400 MBE system and the system was delivered and assembled in late June. In the meantime, we have requested and obtained financial support from the Department of Electrical Engineering and Computer Sciences and the Electronics Research Laboratory for the use of industrial funds towards the renovation and air-conditioning of the MBE room and the purchase or a glove box and a laminar-flow hood. These preparations are necessary in order to provide a clean enrivonment for sample storage, handling, and preparation in the MBE room. The MBE system was baked and a vacuum in the middle to upper 10^{-11} range was obtained. A separate vacuum system was built to bake the crucible and furnace assembly prior to their installation in the MBE system. While the initial work is being carried out by Mr. Maurice Bales, a highly qualified laboratory personnel having extensive experience in the ultra-high vacuum system and in the analytical instruments, graduate students are asked to watch and help in the work process so they can learn the procedure, and more importantly, get a feel of the extreme care needed in the operation. We hope and expect to start the growth process in late September.

Interaction with Other Units

Close interaction is expected with the work in microfabrication under SSD-82-1, SSD-82-2, with the work on material characterization under SSM-82-1 and SSM-82-2, and with the work on injection lasers underQE-82-1.

References

(1) See, for example, B. I. Miller, E. Pinkas, I. Hayashi and R. J. Capik, J. Appl. Phys. 43, 2817 (1972).

(2) R. D. Dupuis and P. D. Dapkus, IEEE J. Quantum Electron. QE-15, 128 (1979).

(3) A. Y. Cho and J. R. Arthur, Progress in Solid State Chemistry, 10, 157 (1975), Pergamon Press.

(4) A. Chandra and L. F. Eastman, "The LPE growth of, and the study of alloy scattering in high purity (GaAl)As," Electronics Materials Conference, paper G-5 (1979).

(5) P. Hiesinger, W. H. Koschel and R. S. Smith, "Optical GaAs layers grown by MBE," Electronic Materials Conference, paper G-7 (1979).

(6) P. K. Vasuder and R. G. Wilson, "Damage gettering of Cr during annealing of Cr and S implants in semi-insulating GaAs," Appl. Phys. Lett. vol. 37, 308 (1980).

(7) P. M. Asbeck, J. Tandon, B. M. Welch, C. A. Evans, Jr., and V. R. Deline, "Effects of Cr redistribution on electrical characteristics of ion-implanted semi-insulating GaAs," EElectron Device Lett., Vol. EDL-1, 35 (1980).

(8) T. J. Magee, J. Hunt, V. R. Deline and C. A. Evans, Jr., "Low temperature gettering of Cr in GaAs," Appl. Phys. Lett. vol. 37, 53 (1980).

(9) C. C. Chang, P. H. Citrin and B. Schwartz, "Chemical preparation of GaAs surfaces and their characterization by Auger electron and x-ray photo-emission spectroscopes," J. Vac. Sci. Technol. 14, 943 (1977).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

II.B Basic Research in Solid State Electronics - Devices — Coordinator: Professor T. Van Duzer

General

Since 1960 solid state device research and integrated circuit research have been carried out in a common facility in the Electronics Research Laboratory. We have long maintained and observed the obvious benefit; everyone enjoys a more complete, flexible experimental capability. Further, as a consequence of sharing experimental facilities, there has been a beneficial contact between researchers in apparently quite different fields. One result is a significant transfer of technique, accelerating progress in experimental technology for all concerned. More subtle results are the development of larger research goals in common.

An excellent example of the interaction of different research groups is the research in electron-beam lithography first begun by Professor Van Duzer and students about 5 years ago. This work was motivated by the need for very fine geometries in Josephson junction structures. This background stimulated work by Professor Neureuther and students in wider problems of lithography, and more recent work undertaken by Professors Neureuther and Oldham to explore advanced lithographies for integrated circuits.

The IC fabrication facility continues as the focal point for the collaboration between the device, design and technology research activities in solid state electronic devices. During the last year the laboratory has been upgraded in capability and cleanliness, with the latest addition being a CANON FPA 141 projection printer funded through NSF and University sources.

The proposals contained herein are all advanced device basic studies which use the common laboratory facilities in the experimental phase. They have in common the state of the art techniques required for successful fabrication. Such processes as ion implantation, high resolution lithography, plasma etching, and ion milling will be used, as well as more standard processes such as diffusion and thin film deposition. The research proposals also have in common certain intermediate and long-term goals. In general the intermediate goals are the basic study and development of simple devices and device models which will point the way toward the long term goal of more powerful, cheaper, denser circuits.

The most basic studies in this proposal are the investigations in advanced lithography. Progress in all the device studies depends in large measure on advances in the definition of the structures. The e-beam studies are aimed at an analytic understanding of the factors controlling the ultimate performance of e-beam lithography systems. The results of such studies would make possible, for example, the application of the extensive Monte Carlo and experimental energy deposition characterization to a wide class of new materials, including, e.g., Josephson superconductor structures. The proposed x-ray and photolithographic studies similarly promise to aid in the advance of the integrated circuit and transducer state of the art.

The proposal on Josephson device studies is aimed at exploring the fundamental limits of the performance of these devices in large scale electronic applications. Van Duzer and co-workers have demonstrated that they can perform submicron lithography in a modified scanning electron microscope. They have also constructed a number of novel working Josephson structures. They now propose to combine the technologies and make really dense circuit cells to explore the problems in this new domain of device size. A number of fundamental theoretical problems will be encountered and resolved (e.g., storage of a single flux quanta appears impossible in the tiniest loops) in the course of these studies; it promises to be a very exciting time in the Josephson effect research.

Another proposal concerns the exploration of novel processes for high performance LSI. This is a continuation of a program which has already demonstrated a unique CMOS process for fabrication of analog and digital circuits on the same chip. In the present proposal emphasis is placed on the search for simpler, denser processes which make use of such tricks as self-alignment to make possible a generation of higher performance, lower power integrated circuits. One largely unexplored circuit approach uses silicon MESFET's as the active devices. In this research, various methods of fabricating MESFET integrated circuits will be explored. The potential reward is very large, as MESFET's are capable of functioning at subnanosecond speeds but with a power-delay product orders of magnitude better than present approaches.

The proposal for noise studies in integrated circuits is aimed at finding new ways of achieving low-noise amplification in integrated circuits. The use of ion implantation to achieve special low-noise bipolar devices, and to fabricate monolithic JFET structures is one avenue which will be pursued. Another area with potentially very large payoff is low-noise MOS devices for all MOS analog circuits. It appears that a significant portion of the rapidly expanding telecommunications IC market can be satisfied with MOS LSI provided low-noise analog amplification can be realized. One approach to be pursued is the use of buried channel MOS. By performing a second implant in the channel, the electrons can be confined to the bulk, which will have the effect of eliminating the noise from surface states.

The final proposal in the device area deals with the need for all-electronic transducers. As electronics has become cheaper, an increasing bottleneck in its application to control problems is the lack of inexpensive transducers. Such transducers often can be based on the piezoelectric effect. The purpose of the project is to develop a novel method for the production of piezoelectric polymer thin films directly from monomer sources, thereby eliminating many of the constraints inherent in incorporating such films into solid state devices.

Significant Progress

Progress in the program supported by JSEP includes:

(1) Measurement of the absorption spectra of several electron-beam resists and photoresists;

(2) Demonstration of a capacitance measurement to determine the remaining resist thickness vs. time during development;

(3) A new technique for noise reduction in switched capacitor filters has been developed.

(4) Observation that depletion-mode devices exhibit a region of buried-channel conduction in which the input-referred flicker noise is greatly reduced.

(5) An experimental[1] low-noise chip has been fabricated containing high-frequency bipolar devices, 3-terminal and 4-terminal high-frequency JFETS as well as compatible I^2L logic.

References/Publications

1. Opportunities with Synchrotron Radiation," A. R. Neureuther, Proc. of the Lithography/Microscopy Beam Line Design Workshop, Feb. 21, 1979, Stanford Synchrotron Radiation Laboratory. Also SSRL Report 79/02.

2. "In Situ Characterization of Positive Resist Development," W. G. Oldham, Optical Engineering, v. 18, n. 1, January-February 1979, pp. 59-62.

3. "Resonances in Semiconductor-Barrier Josephson Junctions," T. Van Duzer and W. Y. Lum, J. Appl. Phys., vol. 49, August 1978, pp. 4560-4563.

4. "Switching Measurements on Josephson Memory Loops," T. Van Duzer, W. Y. Lum and H. W. K. Chan, J. Appl. Phys., v. 49, July 1978, pp. 4302-4303.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSD-81-3 (terminated) — Last Year's No.(s): SSD-80-3

Title: New Integrated Circuit Processes for High-Performance LSI

Senior Principal Investigator(s): D. A. Hodges (415) 642-3948
W. G. Oldham 2-2318

Scientific Objective

The complexity of large-scale integrated circuits continues to grow rapidly. As the dimensions of individual devices are reduced to the submicron range, mask-making and mask alignment become more difficult and costly. We wish to investigate simple new fabrication processes which might provide higher performance devices and circuits than those obtainable with existing processes, while employing fewer masking steps. Other desirable features in potential new processes are a maximum degree of inherent self-alignment of device features and isotropic etching and impurity doping processes to give improved control of device geometries.

State of the Art

Standard fabrication processes for large-scale integrated (LSI) circuits are generally specialized for digital, analog, or charge-coupled device (CCD) functions.[1,2,3] The processes which provide highest circuit density (e.g., I^2L and silicon-gate NMOS) typically have performance limits such that digital logic speeds faster than 5 ns are very hard to achieve, and analog circuit functions are realized only with serious limitations on accuracy and signal-to-noise ratio. The low power consumption of complementary MOS circuits and the unique signal-processing capability of CCD's are obtained only at the expense of complex, specialized fabrication processes. To date, new fabrication processes such as ion implantation, local oxidation, self-aligned masking, plasma and ion etching, and electron-beam pattern definition have been used in the evolutionary improvement of existing integrated circuit processes, without enhancing their mutual compatibility[4,5]. We propose research on new LSI processes which exploit the new fabrication techniques to achieve better circuit versatility and performance.

Progress and Publications

A Si MESFET model for circuit analysis has been derived [8]. It includes the following second order effects:

- Distributed Channel Charge
- Drain Feedback
- Substrate Bias Effects
- Source-Drain Punch-Through
- Variable Capacitance Effects
- Temperature Effects

The model is mostly empirical and has been implemented in the integrated circuit simulation program SPICE 2.

In recent years, there has been an increased interest in GaAs MESFETS for high-speed low-power integrated circuits. However, an accurate device model for circuit analysis is still lacking as drift velocity saturation dominates the characteristics of these devices. Analytical models proposed previously use a coarse approximation of the mobility as a function of the electric field and yield the drain-source current in implicit form. Such solutions are unacceptable for CAD models as they require iteration within the device model.

Progress and Publications, cont'd

We have found an explicit solution for the drain-source current and saturation voltage by approximating the mobility μ, by

$$\mu(E) = \frac{\mu_o}{1 + \frac{\mu_o}{V_{SAT}} E}$$

where μ_o is the low-field mobility, V_{SAT} is the saturated drift velocity, and E is the electric field. This approximation for the mobility is widely used in two-dimensional device simulation programs like CADET. A new general model for JFETs and MEFETs that contains this approximation of the mobility and that also includes the previously mentioned second order effects, subthreshold conduction, and short-length and narrow-width effects, has been derived. The model is mostly physical and a publication of it is in preparation. As the model includes velocity saturation, it is also valid for III-V compound MESFETs like GaAs.

The MESFET model in SPICE 2 has been used to design the following circuits:

- 1 x 1 K BIT SHIFT REGISTER

  Speed : 0-500 M bits/S
  Power : 1.2 W
  Area : 3 x 4 mm^2
  Organization : SPS
  # of Elements : 30,000
  On-chip Clock Drivers
  Fully ECL compatible

- δ x δ BIT AND 10 x 10 BIT PARALLEL MULTIPLIERS

Speed	: 31 ns	δ x δ BIT
Power	: 0.5 W	
Area	: 1.2 x 1.3 mm^2	
Speed	: 39 ns	10x10 BIT
Power	: 0.7 W	
Area	: 1.5 x 1.6 mm^2	

  Organization : CSA, no carry look-ahead
  # of Elements : 2000-3000
  TTL Data Compatible

- SEVERAL SMALL CIRCUITS

  3 Divide-by-two's
  δ Ring Oscillators
  2 Drivers (ECL and TTL)

The shift register serves as a test vehicle for the yield of this new technology. Together with the multipliers, the circuits also demonstrate the low speed-power product of MESFETs in practical applications and the possibility of interfacing to other technologies like ECL and TTL. The

Progress and Publications, cont'd

smaller circuits serve to support a computer study of Si MESFET circuit techniques with experimental data. The work on these circuits is being done in cooperation with Tektronix, Inc., Oregon. Presently the circuits are being fabricated and the first parts are expected in the Fall of 1980.

It should be noted that the above circuits use the "all-depletion" circuit technology and that application of the "enhancement-depletion" technology will significantly reduce the power and area of the above circuits. The latter circuit technology requires, however, a tight control of process parameters.

In order to investigate process parameter variations, a device characterization program has been written. It runs on an automatic device characterization system that uses a Tektronix 4052 as controller and enables the user to (quickly) obtain statistical parameters for a small dimension MESFET model for circuit analysis. All data is stored on disk and is used as a feedback for the process and for further development of the new JFET/MESFET model for CAD.

Significant Accomplishments

A Si MESFET model has been derived [1] and has been implemented in the integrated circuits simulation program SPICE 2. This model contains distributed charge effects, drain feedback, substrate bias effect, source-drain punch-through, variable capacitance effects, and temperature effects.

A newer model has been derived which includes velocity saturation, subthreshold conduction, and small dimension effects in addition to the above. The model is mostly physical and applies to GaAs JFETs and MESFETs as well. A publication of the model is in preparation.

The SPICE 2 MESFET model has been used to design a 1 x 1 k bit static shift register that is an order of magnitude faster than commercially available registers of that size, and δ x δ bit and 10x10 bit parallel multipliers that have an order of magnitude lower power than commercially available multipliers with similar speeds. The work on these circuits is being done jointly with Tektronix, Inc., Oregon, and experimental results are expected in the Fall of 1980.

Interactions with Other Work Units

During the course of this research, interactions with the groups working with Professors W. G. Oldham, A. R. Neureuther, P. R. Gray, R. G. Meyer and R. W. Brodersen were maintained.

References

[1]D. J. Hamilton and W. G. Howard, Basic Integrated Circuit Engineering, McGraw-Hill, 1975.

[2]P. Richman, MOS Field-Effect Transistors and Integrated Circuits, Wiley, 1973.

[3]R. Melen and D. Buss, Eds., Charge-Coupled Devices: Technology and Applications, IEEE Press, 1977.

[4]IEEE Jour. of Solid-State Circuits, Special Issue on Technology and Processing for Integrated Circuits, August, 1976.

[5]IEEE Jour. of Solid-State Circuits, Special Issue on Semiconductor Materials and Processing Technology, August, 1977.

[6]G. Nuzillat et al., "A Subnanosecond Integrated Switching Circuit with MESFETS for LSI," IEEE Jour. Solid State Circuits, SC-11, June 1976, p. 385.

[7]H. Muta, et al., "Femto Joule Logic Circuit With Enhancement-type Schottky Barrier Gate FET," IEEE Trans. Electron Devices, ED-23, September, 1976, p. 1023.

[8]C. D. Hartgring, W. G. Oldham and T. Y. Chiu, "A MESFET Model for Circuit Analysis," Solid State Electronics, 23, pp. 121-126. 1980.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSD-81-1(terminating in part) Last Year's No.(s): SSD-80-1

Title: Research in Advanced Lithographic Techniques for Microcircuits

Senior Principal Investigator(s): A. R. Neureuther (415) 642-4590
W. G. Oldham 2-2318

Scientific Objective

We plan to explore the fundamental limitations in lithography as microcircuit feature sizes decrease. The emphasis in this work is on the exposure and development of ultra-high resolution resists for optical x-ray and e-beam lithography. Exposure models and development models will be formulated based on experimental characterization of resist properties. A major emphasis will be placed on the prediction and characterization of final resist cross-sections. The limits of minimum useful exposure are of key interest.

State of the Art

Lithography

The first major advance in understanding of photolithography came in the series of papers by Dill and co-workers, of which references 1 and 2 are representative. A simple linear model for the single wavelength exposure and development of positive photoresists of the diazo type enabled quantitative predictions of the effects of exposure and development parameters on resist dissolution rate. Very recently the model was applied to a multiwavelength exposure[3]. However, the basic model was not extended to account for nonlinear interaction between the wavelengths, effects which we have observed in our characterization at Berkeley. Because all practical exposure systems are necessarily polychromatic, it is essential to modify the basic resist model to correctly account for multiwavelength exposure interactions.

Negative photoresists, although the dominant factor in IC fabrication, have not been modeled in any comparable fashion to the positive resists. The development process is very complex and it is only recently that quantitative studies of development kinematics have been reported. The most recent and ambitious work is that of Tu and Ouano[4] which models polymer dissolution in general. The particular experimental case examined is etching of polystyrene in MEK, but the results appear applicable to classical negative photoresists. A much simpler negative resist model which ignores the kinematics entirely was proposed by Ko and Oldham and is in the process of being tested at this time[5].

X-ray and e-beam lithography have intrinsically such a very fine resolution capability that an accurate resist model would appear as essential. However, the weak source intensity problem and, in the case of e-beams, the proximity effect both force a very detailed look at exposure and development mechanisms. In fact in both technologies a direct tradeoff exists between exposure time and resolution[6,7]. A figure of merit such as the exposure time-linewidth product depends on the resist material and the exposure and development parameters.

A simple exposure-development model for the classic PMMA resist was proposed by Greeneich[8,9]. This model has been rather successful in predicting x-ray and e-beam produced resist profiles[10,11]. However, the development model, based purely on molecular weight, has recently been questioned[12]. It is suggested, e.g., that resist porosity as produced by gas evolution during exposure plays a role in development kinematics[12]. In this case post exposure processing and developer formulation might be key parameters affecting final

profiles. Resist characterization and derivation of special cases of the kinematic model[4] are required to attack this important problem.

There are very basic problems to be solved in the use of resists at the limits of low exposure. Statistical effects ultimately limit the usefulness of any resist[13]. In the case of x-rays an effective photo electron range has been determined for various x-ray wavelengths[14,15]. A complete distribution function should be determined relating shape and relative numbers of photo electron energy deposition profiles to x-ray wavelength. A statistical model of exposure could then be developed which yields the local three dimensional energy deposition to exposure.

In addition to the statistical effects, long range electron scattering plays a significant limiting role in high resolution e-beam lithography.

Recent work on resist exposure by electrons can be divided into two approaches, analytic modelling based on scattering and energy loss formulae[8], and Monte Carlo calculations carried out in computers. The latter have been refined over the past several years, and yield results in good agreement with experiment[16]. They have the disadvantage that each new physical embodiment requires a new calculation, and each calculation is expensive and time consuming. The results cannot be generalized as easily as analytic formulations, but since the Monte Carlo procedure simulates what actually occurs in the solid, it is potentially as accurate as the cross-sections for scattering that are used, provided enough trajectories are calculated. (We are developing Monte Carlo programs on a different grant for comparison purposes.)

Analytic modelling of the electron interaction with the solid can give relatively simple formulae which are surprisingly accurate given the approximations on which the modelling is based. These easy-to-interpret formulae provide a good physical "feel" for the problem, and can provide accurate numerical results in some cases. Most incorporate the single backscatter model of Everhart[17], the forward-scattering model used by Nosker[18], and the combination of these explored by Greeneich and Van Duzer[19] and by Hawryluk, Hawryluk and Smith[20]. Recently, McAfee[21] and others[22] have extended Everhart's backscattering model. This extension suggests an important avenue for future studies - the formulation of a simple analytic model for energy deposition profiles.

Progress Since last Major Proposal

The emphasis in the second year has been primarily on electron beam lithography with additional work on developing automatic tools for characterizing positive type photoresist. Studies of electron energy dissipation in layered media including a new physical model based on the random nature of inelastic scattering events were completed. A comparison of direct and continuously slowing down approximation Monte Carlo methods for simulating electron scattering was made. Electron beam alignment signals were studied experimentally as well as with suitably modified versions of the Monte Carlo energy deposition simulation programs. An experimental investigation of the use of positivie photoresist AZ1350J as a non-swelling, high-resolution negative electron beam resist was carried out in collaboration with Siemens Corporation. Several improvements in the accuracy of an automatic system

Progress Since Last Major Proposal, cont'd

for measuring the exposure parameters of positive photoresist were made and a method of determining the development parameters through the in situ measurement of absorption was explored. The results of these efforts will now be described in somewhat greater detail.

A new model for electron scattering was introduced into Monte Carlo simulation algorithms. The new model allows random inelastic scattering events and does not assume that the electron is continually losing energy. Thus it is statistically possible for some electrons to pass through thin films without loss of energy as is observed experimentally. Electron dissipation in layered media was also considered particularly as it applies to obtaining very high resolution on thin substrates. Both theory and experiment showed that higher resolution in electron beam lithography can be achieved by using thinner electron sensitive polymer films, higher beam voltages, and thinner substrates. More details are given in the PhD thesis of I. Adesida, entitled "Electron Energy Dissipation in Layered Media," and described by the following:

Abstract

The influence of electron scattering on the resolution of electron beam lithography has been studied theoretically and experimentally. Theoretical calculations of the spatial distribution of electron energy dissipation in a very thin electron sensitive polymer film coated on various thicknesses of silicon substrates have been made using two different Monte Carlo models. Experimentally, we have exposed elementary lithographic patterns on the layered structures mentioned above. Both theory and experiment showed that higher resolution in electron beam lithography can be achieved by using thinner electron sensitive polymer films, higher voltages, and thinner substrates.

Fundamental characteristics of electron penetration through thin films of aluminum and polymethylmethacrylate (PMMA), such as energy distribution of transmitted electrons, were theoretically calculated using two Monte Carlo approaches. One approach is conventional in that the energy loss of the electron along its trajectory is computed using the continuous-slowing-down approximation (CSDA). The essential features of the second approach are the inclusion of the random nature of inelastic scattering events, and also the extension of Gryzinski's semi-empirical expression for core electron excitation to valence electron excitation through the use of an appropriate mean binding energy. A detailed comparison with available experimental results showed that the second Monte Carlo approach gave a more realistic answer for the transmitted electron energy distribution.

In addition, both Monte Carlo approaches were used to calculate the electron energy dissipation profiles in a very thin electron sensitive polymer film ($\sim$ 1000 Å-thick PMMA) on silicon substrates for energetic incident electrons. Energy dissipation profile calculations were made for dot, line, and

Progress Since Last Major Proposal, cont'd

parallel line exposures. The effect of varying the substrate thickness and exposure dosage were studied in detail. The Gaussian scattering parameters n_F, β_b, and β_f were also evaluated theoretically with the CSDA model.

For the experiments, different thicknesses of silicon substrates were fabricated using an anisotropic etching method. Layered samples of thin PMMA film on thin films of silicon were exposed with a stationary beam (dot exposure) and a scanned beam (line exposure). After exposure, the samples were developed, and the resulting relief patterns measured in a scanning electron microscope. Experimental results were compared in detail with results of both Monte Carlo approaches. Agreement between experiment and both Monte Carlo approaches was good, which indicates that both approaches can be used to predict energy dissipation profiles for electron beam lithography. Results also showed that higher resolution in electron beam lithography and a reduction in proximity effect can be attained with a reduction of electron scattering in the exposed sample. The reduction in electron scattering is achieved by using thinner films of electron beam resists and thinner substrates coupled with higher incident electron beam voltages.

To study electron beam alignment signals theoretically, the CSDA Monte Carlo energy deposition algorithms were modified to produce information about electron trajectories in the presence of a tapered step in the substrate material. This nonplanar substrate extension allows for the possibility that electrons which leave the substrate at one point may re-enter the substrate at another position. The algorithms were also modified to collect position and momentum statistics within the substrate as well as the angular and energy statistics of backscattered electrons. The statistical information within the substrate is useful in developing approximate analytical methods of characterizing alignment signals. Good agreement has been obtained between experimental and simulation results for 54.6 degree anisotropically etched registration marks in silicon. Some progress has been made toward generating a normalized or universal curve for characterizing alignment signals as a function of the Bethe range of the electrons. The abstracts of two publications on this subject follow.

The first paper, "Monte Carlo Simulation for Electron Beam Microfabrication" by Lin, Adesida and Neureuther, Appl. Phy. Lett., vol. 36(8), 15 April 1980, is abstracted as follows:

Abstract

Monte Carlo calculations based on a continuous-slowing-down-approximation (CSDA) model have been carried out to study the backscattered electron image formation of a 54.6° tapered etched step registration mark in silicon. It is found that the energy signal gives slightly better contrast and greater average slope than the number signal. The contrast increases with step depth and is very close

Progress Since Last Major Proposal, cont'd

> to its maximum value of 1.4 when the step depth is increased to 40% of the Bethe range of the primary beam. Additional step depth will degrade the signal shape. A universal curve of the average signal slope as a function of the normalized horizontal mark transition is also presented.

The second paper, entitled, "A Study of Alignment Signals for Electron Lithography," by Lin, Adesida and Neureuther, will be presented at the 9th International Conference on Electron and Ion Beams Science and Technology, at St. Louis, Missouri, in October 1980 and is abstracted as follows:

Abstract

> High quality alignment signals are required in electron lithography. In this paper, the Monte Carlo method is used to study the alignment signals formed by electrons that are backscattered from tapered etched silicon marks. Effects of the mark geometry and the incident beam voltage are explored. Universal curves of both the contrast and the average signal slope are obtained. The results indicate that although a step of depth greater than 40% of the Bethe range of the primary beam yields a better contrast, too large a step will result in the decrease of the average slope. The quality of the alignment signal can be improved if the detector is positioned to collect the backscattered electrons with small takeoff angles. The sum and difference signals from detectors in different azimuthal angles are also examined. The results show that in detecting a topographical discontinuity, the difference signal is preferred rather than the sum signal. Experimental confirmation of the theoretical predictions shows good agreement with the universal curve of contrast versus the normalized step depth. The alignment marks were fabricated by using anisotropic etching techniques in silicon, and the measurements were conducted in an ETEC Autoscan SEM.

Interest in the characterization of positive type photoresists has led to the consideration of diazo sensitized novalak based photoresists as negative electron beam resists using image reversal. Experimental exposures were carried out at Siemens Corporation in Munich, Germany, in a collaborative study by W. G. Oldham during his Sabbatical leave. It was found that if the photo active compound is first selectively destroyed in a vacuum exposure by an electron beam, a subsequent flood UV exposure in a wet atmosphere will convert the remaining areas into a highly soluble state. This in effect produces a negative imaging type resist capable of submicron resolution at moderate doses (25 $\mu C/cm^2$ at 20keV) without the usual limitations due to swelling during development.

This work will be published in IEEE Electron Devices Letters, Oct. 1980, and is entitled, "A High Resolution Negative Electron Resist by Image Reversal," by Oldham and Hieke. An abstract of this paper follows:

Progress Since Last Major Proposal, cont'd

Abstract

The use of AZ1350 family photoresists as negative electron resists is described. Conventional photolithographic technology is used to coat and process the resist, with the exception of an e-beam exposure for patterning. A flood UV exposure is used for image reversal. Using 1.5 μm initial thickness, the exposure threshold for 6 s development in 1 : 1 AZ : H_2O developer is 7 $\mu C/cm^2$. The resist contrast under these conditions is 1.3; and the sensitivity is about 25 $\mu C/cm^2$ (70% thickness remaining). Useful resolution on SiO_2/Si and $Al/SiO_2/Si$ substrates is demonstrated to be at least 0.5 μm, and the resist is shown to mask the plasma etching of Al.

Continuing work on developing automatic systems for determining resist parameters advanced on two fronts. The exposure measurement system was revised to include signal averaging to improve the S/N ratio and was modified to allow hard bleaching to more accurately determine the nonbleachable absorption. A new approach for determining the resist development rate by means of measuring the absorption of the remaining resist in situ was explored. Test runs on an experimental apparatus gave extremely noisy data apprently due to the turbulence of the developer solution and the absorption of the dissolved by-products. These experiments are described in "Characterization of Positive Photoresists," the MS thesis of S. Mehotra, which is abstracted herewith:

Abstract

In this report, a model for characterizing positive photoresist is discussed. A computer-aided system for resist measurement is described. Experimental techniques to determine the exposure parameters using the model proposed by Dill and co-workers are explained. A new approach for measuring the development rate as a function of the photoactive active inhibitor concentration is proposed.

Publications

JSEP Support

"Electron Energy Dissipation in Layered Media" - PhD thesis of Ilesanmi Adesida. University of California, 1979

"High Resolution Electron-Beam Lithography on Thin Films" - I. Adesida, T. E. Everhart, and R. Shimizu. Jour. Vac. Sci. Tech., vol. 16(6), pp. 1743-1748. Nov./Dec. 1979.

"Monte Carlo Simulation of Registration Signals for Electron Beam Microfabrication" - Y. C. Lin, I. Adesida and A. R. Neureuther. Appl. Phys. Lett., vol. 36(8), pp. 672-674. 1980.

Publications, cont'd.

JSEP Support, cont'd.

"A Study of Alignment Signals for Electron Lithography," Y. C. Lin, I. Adesida and A. R. Neureuther. Presented at the Electrochemical Society Meeting, St. Louis, Mo., May 1980.

"AZ1350 as a Negative Electron Resist by Image Reversal," E. Hieke and W. G. Oldham, Microelectronics '80, Amsterdam, Oct. 1980.

"A High Resolution Negative Electron Resist by Image Reversal," W. G. Oldham and E. Hieke, to appear in Electron Devices Letters.

"Characterization of Positive Photoresist," Sanjay Mehotra, MS thesis plan II, University of California, June 1980.

Related to JSEP Work

"Direct Observation of Voltage Barriers in Zinc Oxide Varistors," O. L. Krivanek, P. Williams, and Y. C. Lin. 37th Ann. Proc. Electron Microscopy Soc. Amer., San Antonio, Texas, 1979. G. W. Bailey (ed.)

"Exploration of Electron-Beam Writing Strategies and Resist Development Effects," M. G. Rosenfield and A. R. Neureuther, Electrochemical Society Meeting, St. Louis, May 1980.

Significant Accomplishments

A highly accurate Monte Carlo algorithm for calculating electron scattering in solids has been developed. A more physically correct model which allows electron scattering to be considered either as individual inelastic (direct) scattering events or through the continual-slowing-down-approximation (CSDA) has been simulated. Excellent agreement with measurements of electron transmission through thin films was obtained. A significant extension of the Monte Carlo program to allow nonplanar substrates has made it possible to study alignment signals from tapered etched silicon steps. Experimental and theoretical results have shown that to a surprising extent simple empirical universal models can be developed to predict electron beam alignment signals.

A breakthrough in the problem of negative resist swelling and its inherent electron beam resolution has been made. We have demonstrated that a non-swelling positive photoresist (AZ1350J) may be used as a negative electron resist by means of image reversal. Resolution below 1 μm in films 1.2 μm thick was observed at a dose of 25 $\mu C/cm^2$ at 20keV. The high etch resistance in plasma etching is also retained.

Interaction with Other Work Units

We have assisted Professor Van Duzer in the development of a pattern generation system for the ETEC Autoscan electron microscope. We have also interacted with Professor Hess of Chemical Engineering in the testing of PMMA-related resist materials.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSD-81-2 (terminating in part) — Last Year's No.(s): SSD-80-2

Title: Fundamental Limitations of Miniaturization if Josephson Memory and Logic Circuits

Senior Principal Investigator(s): T. Van Duzer (415) 642-3306

Scientific Objective

The objective of this work is to determine the limitations on miniaturization of Josephson digital memory and logic circuits.

State of the Art

For the past decade, work has been in progress on developing the use of Josephson junctions for digital applications. The driving motivation has been the extremely small delay-power products that have been demonstrated. This is a result of the fact that the voltages are in the millivolt range, the currents in the milliampere range, and the circuit switching times less than 10^{-10} s. These low energy levels have been demonstrated with rather large circuits. It is evident that such circuits can be made advantageously in much smaller sizes and that thermal effects may not be the limiting factor.

There have been some limited efforts at miniaturization of Josephson circuits. Josephson junctions as small as 1 μm^2 have been reported[1]. Memory cells with nondestructive readout have been reported with a size of 1.4 mil^2, which is comparable with small present-day semiconductor memory cells[2]. The report of that memory cell also contained some theoretical guidelines for cells storing a substantial number of flux quanta. There have also been reports of single-flux-quantum memory cells with destructive readout[3-5], and some details of their operation have been explained. The space taken by these cells appears to be somewhat less than 1 mil^2. An IBM patent has appeared in 1977 that treats miniaturized memory cells where the need for inductance is satisfied by using very thin films with the attendant kinetic inductance which results from the momentum of the electron pair fluid. There have been no systemmatic miniaturization studies presented of the type made by Keyes[7] for semiconductor devices.

Progress and Publications Since Last Major Proposal

We have not previously concentrated on the miniaturization aspect of Josephson digital circuits, but have recently published several papers on various other aspects of Josephson digital circuits.

With JSEP Support

"Resonances in Semiconductor-Barrier Josephson Junctions," T. Van Duzer and W. Y. Lum, J. Appl. Phys., v. 49, pp. 4560-4563, August 1978.

"Switching Measurements on Josephson Memory Loops," T. Van Duzer, W. Y. Lum and H. W. K. Chan, J. Appl. Phys., v. 49, pp. 4302-4303, July 1978.

Significant Accomplishments

An analysis was made of the smallest possible superconductive cells that can be made using flux quantization. Loops of about one micron diameter formed with 10_2nm thin film lines and containing two Josephson junctions about 0.3 x 0.3 μm^2. The current-transfer time to change states in the loop from a local "0" to a logical "1" will be approximately one picosecond. A limiting factor will be achievable current densities in Josephson junctions.

We have studied the fabrication problems associated with making feature sizes on the order of 0.1 μm. This has resulted in devices for another project based on a novel silicon-coupling arrangement.

Interaction with Other Work Units

This program of studying miniaturization forms a part of a larger effort on various aspects of Josephson digital circuits. A program has been initiated to develop a high-speed A/D converter and this will use Josephson junctions and circuits of conventional size that can be made by photolithography. In that work, we expect to demonstrate superconductive integrated circuits containing some tens of Josephson junctions. Professor A. M. Despain of our Computer Science Division is cooperating in this project. We also have an NSF-sponsored project to study the use of coplanar junctions (both electrodes are in the same plane) with special emphasis on a structure we developed here that involves electron-pair coupling through a highly-doped surface of a semiconductor. These may prove to be valuable for miniaturization and that aspect will be considered.

Our work on Josephson devices and their frequent need for submicron dimensions has given our group a high degree of familiarity with electron lithography and we have published several papers in that field. This expertise will be supported by the microfabrication interests of Professors A. R. Neureuther and W. G. Oldham, as well as the large body of knowledge in our integrated circuits group (SSD-81-1).

DOD Interaction

We have frequent contact with ONR (E. A. Edelsack and R. S. Brandt) and contact with the DOD supporters of the IBM project on Josephson digital circiuts.

References

[1] J. Niemeyer and V. Kose, Appl. Phys. Lett., 29, 380 (1976).

[2] R. F. Broom, W. Jutzi, and Th. O. Mohr, IEEE Trans. Magn., MAG-11, 755 (1975).

[3] H. H. Zappe, Appl. Phys. Lett., 25, 424 (1974).

[4] P. Guerét, Appl. Phys. Lett., 25, 426 (1974).

[5] P. Wolf, SQUID, Superconducting Quantum Interference Devices and their Applications, (H. D. Hahlbohm and H. Lübbig, eds.) Walter de Gruyter, (1977) p. 519.

[6] W. H. Henkels, U.S. Patent No. 4,028,714 (1977).

[7] R. W. Keyes, Proc. IEEE, 63, 740 (1975).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSD-81-4 — Last Year's No.(s): SSD-80-4

Title: Basic Research in Wide-Dynamic Range, Low Noise Amplification Using Monolithic Integrated-Circuit Technology

Senior Principal Investigators(s):

R. W. Brodersen	(415) 642-1779
P. R. Gray	2-5179
R. G. Meyer	2-8026
D. O. Pederson	2-3539

Scientific Objective

To inveatigate new methods of realizing low-noise amplification in monolithic integrated circuits. This will involve work on noise sources and characterization, and on new techniques of circuit design. Technologies employed will include MOS, bipolar and JFET.

State of the Art

Low-noise amplification is a pervasive need in many types of monolithic integrated circuits, both MOS and bipolar. In MOS integrated circuits for example, recent work has shown the possibility of including analog functions such as A/D and D/A conversion on MOS chips containing complex digital circuits such as microprocessors. In another area, it appears that the use of the charge conservation and transfer capability of MOS technology will allow realization of analog filters of low sensitivity and high order in a small die area. Such filters will find wide application in bandwidth compression, speech recognition and communication systems. Common to all these applications is the need for low-noise, wide-dynamicarange amplification using minimum die area [1]. In some cases the realization may take the form of an operational amplifier or an instrumentation amplifier. In other cases, a fixed-gain amplifier (either differential or single-ended) may be the optimum solution. In all cases there are interactions between noise performance and circuit bandwidth, offset, power consumption and die area.

Although analog bipolar circuits are generally in a more mature state than are MOS analog circuits, there is a continuing need for new approaches to the realization of low-noise bipolar integrated circuits. For example, it is still common to find discrete low-noise pre-amplifiers used external to bipolar monolithic circuits in critical applications. The need for low-noise amplification is found both in low-frequency applications where 1/f noise dominates, and also in high-frequency wideband amplifiers [2]. As in the case of MOS circuits, there are interactions between noise performance and other critical circuit parameters.

Progress

Our earlier work on the fabrication, characterization and modeling of generalized multi-layer monolithic structures allowed us to realize a unique monolithic process incorporating high frequency JFET structures with independently accessible gates. Extensive characterization on a range of devices has been undertaken and varified the advantages of these structures for a wide range of high-frequency monolithic filters and real-time signal processing. Experimental high-frequency filters using this process are currently in fabrication. These filters incorporate very-wide-band operational amplifiers (unity gain beyond 100 MHz) made possible by the unique JFET structures described previously. This project will continue with further work in combining advanced fabrication techniques and new system concepts with the ultimate goal being the realization of unique methods of high-speed signal processing using arbitrary combinations of analog and digital techniques.

A second aspect of our work has involved new techniques to achieve maximum possible dynamic range in bipolar and MOS analog amplifiers and signal-processing circuits. Our work in this area has focused initially on methods of achieving maximum dynamic range in switched-capacitor filters. In such devices, the fundamental limit on dynamic range results from thermal noise in the MOS switch transistors used in the filter structure, but monolithic switched-capacitor filters produced to date have not approached this limit because of the dominant effects of flicker noise in the MOS transistors making up the operational amplifiers [1,2]. Our research has resulted in a new differential chopper-stabilized technique which removes this 1/f noise, resulting in experimental fifth-order filter prototypes with dynamic range in excess of 105 dB. This is more than 15 dB higher than previously reported performance obtained from such filters [3]. We expect to continue this work with the objective of exploring the maximum theoretical dynamic ranges achievable, and formulating detailed theories of the noise performance of such filters.

Accomplishments

The paper entitled, "Design Techniques for MOS Switched Capacitor Ladder Filters," by Gordon M. Jacobs, David J. Allstot, Paul Gray and Robert W. Brodersen received the W. R. G. Baker Prize Paper Award. The research reported in this paper is based in part on this work unit. An abstract of the paper follows:

> Design techniquest for monolithic, high-precision, MOS sampled-data active-ladder filters are described. Switched capacitor integrators are used to implement the "leapfrog" configuration for simulating doubly terminated LC ladder networks. Techniques are presented for designing all-pole low-pass filters, as well as methods for including transmission zeros. An approach for implementing bandpass filters is described which is derived from the conventional low-pass-to-bandpass transportation. Monolithic realizations for two different low-pass filters are briefly described which show excellent agreement with theory.

Other accomplishments include the following:

1. A new high-frequency bipolar monolithic process has been devised and extensively characterized for both low-frequency and high-frequency parameters. This research has led to new circuit configurations for high-frequency monolithic filters, switches and amplifiers which are currently being fabricated.

2. A new differential chopper-stabilized switched-capacitor filtering technique was developed, and evaluated by fabricating a monolithic prototype. This fifth-order lowpass 3.5 kHz filter displayed a dynamic range in excess of 105 dB.

Publications

A. Under JSEP

1. G. M. Jacobs, D. J. Allstot, R. W. Brodersen and P. R. Gray,

Publications, cont'd.

A. Under JSEP, cont'd.

1. cont'd.
"Design Techniques for MOS Switched Capacitor Ladder Filters," IEEE Trans. on Circuits and Systems, Vol. CAS-25, No. 12, Dec. 1978, pp. 1014-1021. Received the W.R.G. Baker Prize Paper Award from IEEE.

2. S. K. Lui and R. G. Meyer, "High Frequency Bipolar-JFET-I^2L Process," submitted to International Electron Devices Conference, 1980.

3. K. C. Hsieh and P. R. Gray, "A Wide Dynamic Range Differential Chopper-Stabilized Switched-Capacitor Filter," submitted to 1981 International Solid-State Circuits Conference.

B. Under Other Sponsorship

1. S. K. Lium, R. G. Meyer and N. Kwan, "An Ion-Implanted Sub-Surface Monolithic Zener Diode," IEEE Journal Solid-State Circuits, Vol. SC-14, No. 4, August 1979, pp. 782-784.

2. D. J. Allstot, R. W. Brodersen and P. R. Gray, "An Electrically Programmable Switched-Capacitor Filter," IEEE Journal Solid-State Circuits, Vol. SC-14, No. 6, Dec. 1979, pp. 1034-1041.

References

[1] D. J. Allstot, R. W. Brodersen and P. R. Gary, "MOS Switched Capacitor Ladder Filters," IEEE Journal Solid-State Circuits, Vol. SC-13, No. 6, Dec. 1978, pp. 806-814.

[2] D. Senderowicz, D. H. Hodges and P. R. Gray, "High-Performance NMOS Operational Amplifiers," IEEE Journal Solid-State Circuits, Vol. SC-13, No. 6, Dec. 1978, pp. 760-766.

[3] P. R. Gray. D. Senderowicz, H. O'Hara and B. Warren, "A Single-Chip NMOS Dual Channel Filter for PCM Telephony Applications," IEEE Journal Solid-State Circuits, Vol. SC-14, No. 6, Dec. 1979, pp. 981-991.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: SSD-81-5 — Last Year's No.(s): SSD-80-Supp. (1)

Title: Research on Electronic Systems Composed of Polymer Films and Planar Si Devices for Transducer Applications

Senior Principal Investigator(s): D. W. Hess (415) 642-4862
R. S. Muller 2-0614

Scientific Objectives

We propose to investigate the technology for, and the physical behavior of electronic systems that are composed of polymer-film materials and integrated-circuit devices. The objectives are to define the materials and interface properties and to evaluate the technologies that may ultimately find application to new and improved transducer devices.

Major task:

To investigate the control of piezoelectric properties in poly-vinylidene fluoride and poly-acrylonitrile that can be achieved through plasma-initiated polymerization. The purpose of this effort will be to develop a novel method for the production for piezoelectric polymer thin films directly from monomer sources, thereby eliminating many of the constraints inherent in incorporating such films into solid state devices. This study is based upon current work in our laboratory which demonstrates the feasibility of preparing films of vinyl polymers from monomer sources.

State of the Art

The above task is proposed in order to apply newly developed polymer formation technology (1, 2) to poly-vinylidene fluoride (and possibly poly-acrylonitrile), a polymer material that has very interesting and useful piezoelectric properties (3, 4). The technique of plasma-initiated polymerization (1, 2) has been demonstrated for certain vinyl monomers in bulk condensed phases, but has not been attempted for thin film formation. Our experience with piezoelectric films, particularly with ZnO, has given us a background in exploitation of this property in novel transducers. We expect to show that the plasma-initiated polymerization process can permit tailoring of the piezoelectric activity of the film in order to optimize certain transducer behavior.

Progress to Date

A parallel plate plasma initiated polymerization reactor has been designed and fabricated. The reactor consists of two three-inch diameter parallel plate electrodes mounted in a vacuum chamber. Monomer vapor and inert gases enter the reactor through the upper electrode, and the lower electrode supports the substrate to be coated with polymer. A 13.5 mHz radio frequency generator is attached to the system, and a plasma can be generated between the electrodes.

Significant Accomplishments

The above equipment will be used to test the feasibility of directly forming piezoelectric films from monomer vapor. This technique offers the potential for eliminating the normally separate stretching and poling process steps.

Update of Current Period

A glass vacuum system has been designed and constructed. This system will allow plasma initiated polymers to be formed in the bulk phase (1, 2).

Subsequently, these polymers can be applied to substrates during polymerization using spin-on techniques. The bulk polymerization represents an important complimentary process to the direct film formation technique described above. In combination, the two techniques should allow the formation of polymer films that span a wide range of physical properties such as molecular weight and crystallinity.

During the coming year, preliminary studies will examine the manner in which processing conditions affect the physical properties of plasma initiated polyvinylidene fluoride and polyacrylonitrile films. The physical properties of these films will be correlated with the relative piezoelectric strength of these films. The relative piezoelectric strength of the films will be initially studied in our laboratory by measuring the voltage generated across a film when it is mechanically strained by another transducer (5).

References

1. Y. Osada, A. T. Bell, and M. Shen, Polymer Letters, 16, 309 (1978).

2. Y. Osada, M. Shen, and A. T. Bell, ibid., 16, 669 (1978).

3. R. Hayakawa and Y. Wada, Adv. Polymer Sci., 11, 1 (1973).

4. R. G. Kepler, Ann. Rev. Phys. Chem., 29, 497 (1978).

5. M. G. Broadhurst and G. T. Davis, In Electrets, ed. by G. M. Sessler, Springer-Verlag, 1980, p. 285.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

IV. Basic Research in Information Systems — Coordinator: Professor C.A. Desoer

General

About twenty years ago, the unity of the basic concepts and techniques underpinning the fundamental study of circuits, control systems and communication systems became apparent and became known as system theory. With rapidly increasing power and decreasing cost of computing, these concepts and techniques were applied to larger and larger systems. This commonality of basic theoretical tools and approaches still exists today and as the size the system under study increases, the nature of the problem changes.

These features are particularly apparent in the first pair of topics which cover respectively large circuits and large control systems. In each of these topics we see a fundamental interweaving of decomposition techniques -- such as diakoptic analysis, graphical decomposition by strongly connected components and minimum essential sets, and decentralized control by creation of a hierarchy --, modeling techniques -- piecewise linear and spline approximations -- and analytical techniques.

The third topic is a bold project aimed at stepping out of the by-now-traditional use of simulation for computer-aided electronic circuit design and reaching for a more sophisticated level where the simulation is coupled with up-to-date optimization algorithms to direct the design toward a minimum of a previously chosen objective function or towards the display of a trade-off curve (or surface), so that the engineer, using additional data not present in the mathematical formulation, can choose what he deems to be optimum. A significant feature of the optimization algorithm is that inequality constraints may easily be imposed, a fact which we consider crucial in engineering design.

The fourth topic addresses itself to signal processing; in particular, two dimensional adaptive signal processing. It is proposed to stimulate the synergism of competence in information theory, in algorithms and discrete transforms, and in LSI digital design to pitch tracking transform coding of speech -- by applying to speech two-dimensional signal processing,-- to the implementation of the Winograd Fourier transform algorithm to two-dimensional digital filter design, to the efficient representation of objects within two-dimensional images, and finally to the adaptive recognition of signals.

To anyone who studies these four proposals it is clear that in the course of the work there will be ample opportunities for interaction and cross-fertilization, both through normal informal contacts and through regular seminars.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

III. Basic Research in Quantum Electronics and Optics — Coordinator: Professor J. R. Whinnery

General

Our proposed program in quantum electronics and optics emphasizes the fundamental problems of devices for generation and detection of radiation at wavelengths shorter than microwave. Much of the work deals with extremely novel devices whose potentials are being explored: these include the Josephson and super-Schottky diodes, and the metal-barrier-metal (MBM) junction. Other devices in the proposed study, such as (GaAl)As lasers and high-frequency Schottky diodes, are already known, and the emphasis is on better understanding of their fundamentals and on possible new applications.

There is a need for better mixer diodes at wavelengths between 10 microns and a few millimeters. In the millimeter and submillimeter ranges, cryo-devices (Josephson and super-Schottky junctions) have promise because of their high degree of nonlinearity, but serious coupling problems remain. At somewhat shorter wavelengths (perhaps 30-500 microns) Schottky diodes appear promising but as yet are many orders of magnitude away from their theoretical potential. At still shorter wavelengths, metal-barrier-metal junctions probably are the best potential mixers, but their promise is also as yet largely unexplored. We feel that an attack on the fundamental problem of radiation in-coupling is in order, based on the use of antennas, novel waveguides, and mixer arrays. The devices mentioned above appear to lend themselves to these techniques, and if better coupling can be accomplished the potential of the devices can be realized.

The metal-barrier-metal junction is interesting because it probably has the highest frequency cutoff of any known lumped circuit element. It is believed that it operates by virtue of ac currents at frequency as high as the visible. This encourages us to look for novel ways to exploit such properties. One part of the proposed work has to do with the addition of a second "collector" junction so as to determine whether a transistor-like three-element device is possible. This work also involves fundamental studies of the MBM junction and its mechanism.

The semiconductor laser is, of course a well-known device of great importance. Single-mode operation will make it still more useful, and much has been accomplished here and elsewhere, but the fundamental physical mechanisms of mode supression are still not clear, and studies of them will continue, with emphasis on carrier diffusion. The study of coupled oscillators, for use as phased array sources of radiation, will continue.

The research program being proposed is closely related with work under other sponsorship and to the work of other units. (1) The mixer-array studies will involve use of such devices fabricated under other sponsorship. Progress with the coupling studies will provide guidance for the fabrication work. There is also close relationship with the electromagnetic theory unit

of this proposal; certain fundamental problems of electromagnetics have been raised by the problem of coupling to mixers, and their solution will contribute to achievement of the goals proposed here. There is also considerable interest in millimeter/infrared heterodyne detection in the Departments of Physics and Astronomy at this university. We have been maintaining contact and plan to continue, as this provides guidance as to the state of the art and as to what improvements are required. Considerable work on development and fabrication of semiconductor lasers is being carried on in our laboratory under other support, and techniques made available by that work will facilitate the more fundamental studies and experimental in this proposal. There is also close cooperation between the two projects in Quantum Electronics and Optics.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: QE-81-1 (terminating in part) Last Year's No.(s): QE-80-1

Title: Thin-Film and Guided-Wave Active Optical Devices

Senior Principal Investigator(s):

S. Wang	(415) 642-4134
J. R. Whinnery	2-1030
T. K. Gustafson	2-3139

Scientific Ojectives

We propose to explore and to study novel and complex semiconductor-laser structures for tunability and traveling-wave operation. Theoretical analysis based on scattering-matrix formalism will be carried out to gain insight on possible modes of oscillation in complex laser structures and to guide us in the search for new laser structures. Experimental techniques using LPE and MBE will be developed to fabricate the various structures. Our objectives are (1) to advance the semiconductor-laser technology beyond its present state as an individual coherent optical source, (2) to explore new modes of operation for a semiconductor laser other than the simple Fabry-Perot mode, and (3) to study laser performance when interacting with other lasers or an integrated-optical network.

State of the Art

In recent years important advances in semiconductor lasers have been reported in the attainment of linear light-output versus input-current relation, stable transverse and lateral mode pattern, and single longitudinal mode operation. Equally impressive are achievements in guided-wave optical circuit elements such as directional couplers switches and modulators. However, except for some interesting work on arrays [1,2] most of the research efforts on semiconductor lasers and waveguide optical elements have been limited to the performance and characteristics of individual devices. To expand the usefulness of these devices and to explore the potential as well as limitations of integrated optics, these devices must be studied in the frame of an optical network. We believe that it is opportune to apply the knowledge accumulated and the techniques developed for the microwaves to the advancement of guided-wave optical systems involving sources and other optical elements.

One major advance in semiconductor-laser technology is the incorporation of two-dimensional waveguiding in the transverse plane of the laser structure. During the past few years, many lasers exhibiting stable transverse and lateral mode pattern and single longitudinal mode operation have been developed at several laboratories. These include the buried-heterostructure (BH) laser [3,4], the channeled-substrate-planar (CSP) laser [5,6], and the laser utilizing thickness variation in the grown layer to provide waveguiding in the lateral direction [7-10]. Among the lasers referenced here are the IRW laser [1], the CJSF laser [7] and the narrow DCC-CSP laser [6] being developed and studied in our laboratory. All the lasers mentioned above oscillate in well defined cavity modes in all three directions, transvers, lateral, and longitudinal. This fact facilitates the application of waveguide-network theory to semiconductor lasers and makes possible an analysis of laser structures more complex than the simple Fabry-Perot structure which has been almost exclusively employed in the semiconductor lasers thus far.

In the meantime, remarkable progress has also been made in the fabrication and control of modes in optical waveguides. Low-loss, single-mode waveguides have been reported in GaAs [11] and $LiNbO_3$ [12], and active waveguide devices using coupled guides and Y junctions either alone or in the Mach-Zehnder interferometer configuration have been

developed. These advances further support our view that single-mode guided-wave technology is ready for the exploration of new and complex semiconductor-laser structures and the development of simple integrated optical systems involving the source and other optical elements. On the other hand, when semiconductor lasers are used in practical systems such as in conjunction with optical fibers, practical problems, such as induced pulsation in the laser output, do arise. The problems caused by feedback are well known in network theory. Therefore, it seems timely that we utilize the vast amount of knowledge in waveguide network theory in advancing the state of semiconductor lasers beyond its present state as individual sources and in analyzing and overcoming problems encountered in practical systems.

Much of the theory of microwave networks [13] is directly applicable, since both microwave and optical networks are distributed electromagnetic systems with waveguide modes acting as input and output ports. The known limitations on scattering-matrix parameters [13] must be considered as constraints on the system. Optical parallel to most of the passive microwave-network elements --- hybrids, filters, isolators, power dividers --- have been worked out in integrated optic form, but not all in a form directly integrable with the semiconductor lasers. Moreover, new fabrication techniques such as MBE will permit still different configurations of these elements. Elegant theoretical analyses of the behavior of certain specific junctions have been made [14], but again not for all that are appropriate to the specific configurations or fabrication techniques. Thus much remains to be done on the network aspect of this problem.

Progress to Date

During the period October 1978 - September 1980, a major effort was devoted to a study of the mode-stability problem in semiconductor lasers and the development of a mode-stabilized laser, the narrow DCC-CSP laser. The idea behind the laser can be summarized as follows. If the width of active region is made small compared to the carrier diffusion-length, the effect of hole burning (which is a major cause for lateral mode instability) caused by stimulated emission can be greatly reduced through carrier diffusion. The approaches taken in implementing the idea are (1) the use of a narrow channel (2 μm) smaller than the carrier diffusion length and (2) the use of a double-current-confinement (DCC) scheme to confine the injection current to the narrow channel region. A series of publications have resulted from this investigation which are listed under Publications. The outstanding features of the laser are presented under Significant Accomplishments. Now that we have acquired an understanding of the mode-instability problem and have developed a laser with excellent mode stability which oscillates in a well-defined cavity mode, we can move to a new and exciting phase of our research on combining semiconductor-laser technology and waveguide-network techniques (developed for microwave) for exploration of this relatively unexplored area.

A theoretical study has been initiated on the proper modes of oscillation for two complex laser structures: one with a branch waveguide, and the other with a ring waveguide, attached to a straight

Fabry-Perot cavity. The former structure is to provide longitudinal-mode discrimination and hence wavelength selectivity for the laser while the latter structure is to support traveling-wave lasing modes in the laser in contrast to standing-wave modes in the conventional Fabry-Perot laser. Scattering-matrix formalism is used to relate the inputs to the outputs of the laser structures. The proper longitudinal mode of oscillation can be found by setting the determinant of the scattering matrix to zero (meaning nonzero outputs with zero inputs).

Analytical results on the wavelength-selective laser are very encouraging. The oscillation condition for such a laser is given by

$$R^2 P_1^2 (P_2^2 T_2 + P_3^2 T_3) = 1 \tag{1}$$

where R is reflection coefficient at the three exit facets (two for the Fabry-Perot cavity and one for the branch waveguide), P is the appropriate propagation factor in each segment of the composite laser structure, and T_2 and T_3 represent the transmission coefficient for each branch at the waveguide junction. The above equation can be re-arranged into the familiar form $R_{eff}^2 P_1^2 P_2^2 = 1$ with an effective reflection coefficient

$$R_{eff}^2 = R^2 (T_2 + T_3 P_3^2 / P_2^2) \tag{2}$$

Note that the propagation factors P_3 and P_2 contain both magnitude and phase. The quantity R_{eff} reaches a maximum when the two phase factors are in phase and is a minimum when the two phase factors are out of phase. Therefore, the interference of the two fields at the waveguide junction effectively modulates the threshold condition of the laser, and thus provides wavelength selection for the laser. We should point out that wavelength selectivity is lost if $P_3 = P_2$. For wavelength selectivity to be most effective, the laser structure should be so designed that P_2 and P_3 are in phase only at one wavelength over the spectral width of the gain profile.

Experimental work on the wavelength-selective laser is under preparation. The first structure to be tested will be one with the branch waveguide made of a quarter-ring waveguide. The circular waveguide is chosen in order to make the two parts asymmetrical so that a phase P_2 not identical to phase P_3 is guaranteed. The analytical work on the traveling-wave laser is somewhat more complicated. Preliminary results indicate that the laser output can can be made to contain predominantly one traveling-wave component of the ring cavity, either clockwise or counterclockwise. More work is needed to assure the correctness of the results and to put the results in a form most easily interpretable.

Progress to Date, cont'd

During the past year, we have also investigated the metal-oxide barrier in its potential for an optical amplifier. This has included analysis of the MOMOM structure, studies of coupling into the tunneling region through the surface wave of the metallic portion, and development of an "edge-diode" configuration which gave an interaction area or the same order as a point contact diode (10^{-10} cm^2) but with the stability of integrated-optics configurations. The configuration has since been used to advantage in small superconductivity configurations. Pinholes were a problem in the thin films needed for the MOMOM device, but it is believed that the new molecular-beam epitaxy unit will minimize these. There are many more fundamental problems before it can be determined if optical amplification in this device is a possibility, but as these are also applicable to the detection and mixing problem, they will be carried out in the next work period in the work related to metal-barrier-metal detectors and mixers.

Publications

A. Under JSEP

L. Figueroa, "GaAs Double-Heterostructure Injection Lasers with Lateral Optical and Current Confinement," Ph.D. thesis, University of California, Berkeley, November 1978.

C. Y. Chen, "Control of Lateral and Longitudinal Modes of the GaAs/$Ga_{1-x}Al_xAs$ Semiconductor Laser," Ph.D. thesis, University of California, Berkeley, September 1980.

B. Under Combined Sponsorship

C. Y. Chen and S. Wang, "Narrow Double-Current-Confinement Channeled-Substrate-Planar Laser Fabricated by Double Etching Technique," paper 16.6 Conference Proceedings, Post deadline papers, Second International Conference on Integrated Optics and Optical Fiber Communication, Amsterdam, September 17-19, 1979.

C. Y. Chen and S. Wang, "Narrow-Channel Double-Current-Confinement CSP Laser and Effect of the Current Distribution on Its Performance," paper MCI, Technical Digest, Topical Meeting on Integrated and Guided-Wave Optics, Incline Village, Nevada, January 28-30, 1980.

C. Y. Chen and S. Wang, "Double Etching Technique for the Fabrication of Submicron Channels on a GaAs Wafer and Its Application to Laser Fabrication," Jour. Appl. Phys., vol. 51, pp. 1802-1808, 1980.

C. Y. Chen and S. Wang, "Narrow Double-Current-Confinement Channeled-Substrate-Planar Laser Fabricated by Double Etching Technique," Appl. Phys. Lett., vol. 36, pp. 634-636, 1980.

Publications, cont'd

B. Under Combined Sponsorship, cont'd.

C. Y. Chen and S. Wang, "Near-Field and Beam-Waist Position of the Semiconductor Laser with a Channeled-Substrate Planar Structure," Appl. Phys. Lett., vol. 37, pp. 257-260, 1980.

Invited paper, S. Wang, C. Y. Chen, A. S. H. Liao, and L. Figueroa, "Control of Modal Behavior in Semiconductor Lasers," under preparation for Jour. Quantum Electronics.

Significant Accomplishments

We have developed a double-etching technique (DET) to make grooves of micron and submicron dimensions using conventional photolithography. Grooves having channel width as small as 0.8 μm have been made with uniform quality and the results are reproducible. Using the technique, we have developed a new laser structure, the narrow DCC-CSP laser in which the active region is confined to a half-width comparable to or smaller than the diffusion length. By so doing we minimize the effect of hole burning and by utilizing the built-in index difference provided by the differential loss in the CSP laser, we have been able to achieve excellent lateral-mode stability. The narrow DCC-CSP laser shows linear light-current relation and stable fundamental mode in both transverse and lateral directions up to $5I_{th}$ (the limit of catastrophic damage) and single longitudinal mode up to $2.2I_{th}$ (the highest reported in the literature). An experiment on a new laser structure, the TEPOSE laser with two electrodes for pumping and one electrode for stimulated emission is devised to study the effect of nonuniform and asymmetric current distribution as a result of unequal excitation of the electrodes. It is found that asymmetric current distribution can degrade the fundamental lateral-mode behavior and nonuniform current distribution can lead to multiple longitudinal-mode operation. This study demonstrates the importance of uniform and symmetric excitation as a controlling element to mode stability in addition to built-in index difference. An experiment is also established for measuring the beam-waist width and the beam-waist position to ascertain the guiding mechanism in a semiconductor laser and to observe the stability of the laser characteristics as a function of the pumping current. We have been asked by the Editor of Jour. Quantum Electronics to write an invited paper on the subject of control of modal behavior in semiconductor lasers.

The edge-diode configuration developed for the MOM devices has been widely used in these and in Josephson junction devices.

Interaction with Other Work Unit

Frequent consultation is anticipated with the work unit on electromagnetics concerning wave propagation in dielectric waveguides.

References

(1) D. R. Scifres, R. D. Burnham, and W. Streifer, "Phase-Locked Semiconductor Laser Array," Appl. Phys. Lett., vol. 33, 15, pp. 1015-1017, December 1978.

References, cont'd

(2) W. T. Tsang, R. A. Logan, and R. P. Salathe, "A Densely Packed Linear Array of GaAs-$Al_xGa_{1-x}As$ Strip Buried Heterostructure Laser," Appl. Phys. Lett., vol. 34, 15, pp. 162-165, January 1979.

(3) T. Tsukada, "GaAs-$Ga_{1-x}Al_xAs$ Buried-Heterostructure Injection Lasers," Jour. Appl. Phys., vol. 45, pp. 4899-4906, 1974.

(4) W. T. Tsang, R. A. Logan, and M. Ilegems, "High-Power Fundamental-Transverse-Mode Stripe Buried Heterostructure Lasers with Linear Light-Current Characteristics," Appl. Phys. Lett., vol. 32, pp. 311-314, 1978.

(5) K. Aiki, M. Nakamura, T. Kuroda, J. Umeda, R. Ito, N. Chinone, and M. Maeda, "Transverse Mode Stabilized AlGaAs Injection Lasers with Channeled-Substrate-Planar Structure," IEEE Jour. Quant. Elect., vol. QE-14, pp. 89-94, 1978.

(6) C. Y. Chen and S. Wang, "Narrow Double-Current-Confinement Channel-Substrate-Planar Laser Fabricated by Double-Etching Technique," Appl. Phys. Lett., vol. 36, pp. 634-636, April 15, 1980.

(7) L. Figueroa and S. Wang, "Inverted-Ridge-Waveguide Double Heterostructure Laser with Current and Lateral Optical Confinement," Appl. Phys. Lett., vol. 31, pp. 122-124, 1977; "Curved-Junction Stabilized Filament (CJSF) Double-Heterostructure Injection Lasers," Appl. Phys. Lett., vol. 32, pp. 85-87, 1978.

(8) R. D. Burnham, D. R. Scifres, W. Streifer, and E. Peled, "Nonplanar Large Optical Cavity GaAs/GaAlAs Semiconductor Laser," Appl. Phys. Lett., vol. 35, pp. 734-736, 1979.

(9) T. Sugino, K. Itoh, M. Wada, H. Shimizu, and I. Teramoto, "Fundamental Transverse and Longitudinal Mode Oscillation in Terraced Substrate GaAs-(GaAl)As Lasers," IEEE Jour. Quant. Elect., vol. QE-15, pp. 714-718, 1979.

(10) T. Furuse, I. Sakuma, Y. Ide, K. Nishida, and F. Saito, "Transverse Mode Stabilized AlGaAs DH Laser Having A Built-In Plano-Convex Waveguide," paper 2.2 Proceedings of Optical Communication Conference, Amsterdam, September 17-19, 1979.

(11) J. C. Shelton, F. K. Reinhart, and R. A. Logan, "Characteristics of Rib Waveguides in AlGaAs," Jour. Appl. Phys., vol. 50, pp. 6675-6687, 1979; F. J. Leonberger, J. P. Donnely, and C. O. Buzler, "Wavelength Dependence of GaAs Directional Couplers and Electrooptic Switches," Appl. Optics, vol. 17, pp. 2250-2254, 1978.

(12) I. P. Kaminow and L. W. Stulz, "Loss in Cleaved Ti-Diffused $LiNbO_3$ Waveguides," Appl. Phys. Lett., vol. 33, pp. 62-64, 1978; R. C. Alferness, R. v. Schmidt, and E. H. Turner, "Characteristics of Ti-Diffused Lithium Niobate Optical Directional Couplers," Appl. Optics, vol. 18, pp. 4012-4016, 1979.

References, concluded

(13) See for example, R. N. Ghose, Microwave Circuit Theory and Analysis, McGraw-Hill, p. 212, 1963.

(14) W. K. Burns and A. F. Milton, "An Analytic Solution for Mode Coupling in Optical Waveguide Branches," IEEE Jour. Quant. Elect., vol. QE-16, pp. 446-454, April 1980.

(15) C. Risch, C. Voumard, F. K. Reinhart, and R. Salathe, "External-Cavity-Induced Nonlinearities in the Light Versus Current Characteristic of (GaAl)As Continuous-Wave Diode Lasers," IEEE Jour. Quant. Elect., vol. QE-13, pp. 692-696, 1977.

(16) A. S. H. Liao and S. Wang, "Semiconductor Injection Lasers with a Circular Resonator," Appl. Phys. Lett., vol. 36, pp. 353-356, 1980.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: QE-81-2 — Last Year's No.(s): QE-80-2

Title: Millimeter and Infrared Heterodyne Mixing and Detection

Senior Principal Investigator(s):		
	T. K. Gustafson	(415) 642-3139
	S. E. Schwarz	2-5684
	T. Van Duzer	2-3306

Scientific Objective

In this project we propose to study radiation detection systems involving direct detection and superheterodyne mixing techniques using various nonlinear devices for mixers and detectors. The wavelength range of interest is the entire band of frequencies from millimeter through far infrared, that is 10 mm to 10 microns wavelength. It is of particular interest to understand which techniques are favored --- in the framework of realistic receiver systems --- for application in various parts of the frequency range. The investigation will involve coupling of radiation to devices with impedance matching, selection of the best devices and obtaining their characteristic parameters, and a study of optimal coupling to intermediate-frequency amplifiers. Objectives include low-noise receiver performance, plus other advantages such as wideband response and, for some devices, room-temperature operation. The novel devices in question (being developed partially under other sponsorship) include planar Schottky diodes, super-Schottky diodes, cryogenic SIS and Josephson junctions, metal-barrier-metal diodes, and novel configurations of other, more conventional detectors. Attention will be given to principles of coupling to multiple-device arrays.

State of the Art

The noise temperatures of mixer-IF amplifier combinations have been surveyed for the frequency range 1 GHz (wavelengths of 30 cm to 0.3 cm) [1]. Room temperature mixers are usually Schottky diodes in this range and their best noise properties are typified by a measurement by Kerr [2] at 100 GHz; assuming an IF amplifier with a 15 K noise temperature, the single-sideband noise temperature for the mixer-IF amplifier combination is about 550 K. Equivalently, this is a minimum detectable power of 0.76×10^{-20} W/Hz. That value was then further reduced by nearly a factor of two by cooling the diode (essentially the same results are achieved at T = 18 K or T = 77 K).

To achieve large reductions of noise temperature for frequencies in the several-millimeter wavelength range, superconductive devices must be used. There are two general categories. In one, the Josephson effects are employed and in the other, the nonlinearity that comes with single-particle tunneling in superconductors. The best results obtained with the Josephson devices have mixer noise temperatures in the range of 20-50 times the liquid-helium bath temperature with conversion efficiencies in the range of 0.5-1.4. Mixer noise temperature of 54 K with conversion efficiency of 1.4 at 36 GHz [3], and 140 K with conversion gain of 2.4 at 140 GHz [4] have been achieved. Opinion now is that the Josephson devices have too much noise down-converted into the IF range by beating of the RF noise with the many harmonics of the LO signal and the Josephson oscillations. Still, Taur estimates from detailed computer calculations that a receiver noise temperature of 70 K should be achievable for a SSB receiver at 100 GHz, assuming an IF amplifier with a 20 K noise temperature [5].

Considerable emphasis is now being placed on the "quasiparticle" (single particle) tunneling devices, also known as NIS and SIS junctions. This has grown out of the realization that very strong nonlinearities of the I-V characteristic are available for classical

resistive mixing through the use of devices that function at millivolt levels where a sharp change of slope results from the existence of the superconducting energy gap. The experimental work has been further inspired by the quantum-mechanical analysis of Tucker [6] showing that a resistive mixer can be expected to give quantum-limited detection sensitivities at high frequencies (>70 GHz). It has also shown that conversion gain can be expected from these devices. The earliest of the quasiparticle devices was the super-Schottky diode, which is a Schottky diode with the metal electrode replaced by a superconductor. These showed the best diode noise temperature ever seen at 10 GHz [8]. In the usual configuration, the series resistance leads to a parasitic conversion loss which increases strongly with frequency so that usefulness of the device is limited to wavelengths longer than several millimeters. In the normal metal-insulator-superconductor (NIS) tunneling device, the Schottky barrier is replaced by that of the insulator, and the series resistance is largely eliminated. The same applies in the case of the superconductor-insulator-superconductor (SIS) junction; in this device, the nonlinearity is stronger but it also has Josephson current which can add noise. Results to date on the SIS and NIS junctions have been excellent [9]. Experiments with SIS junctions at 36 GHz have demonstrated the predicted conversion efficiency. The single-sideband value of 0.7 (or 1.4 in DSB) is greater than can be expected from classical mixing theory. The mixer noise temperature of 3 K (SSB) is very close to the photon noise limit $h\nu/k_B = 1.7$. These experiments were done with lead-alloy oxide-barrier-junctions. It would be advantageous to use a more rugged system such as niobium on thin silicon membranes.

The highest frequency at which the quasiparticle mixers have been reported is 115 GHz where a conversion efficiency of 0.2 and a mixer noise temperature of less than about 80 K were deduced from a receiver noise temperature of 470 K. One part of our work is aimed at making an antenna-coupled mixer at one millimeter wavelength; the first measurements shall be at 70 GHz. Carrying the advantages of these devices to the submillimeter wavelength range is a large and important task.

At wavelengths near 10 microns, extrinsic and intrinsic photoconductive and photovoltaic detectors can be used as mixers. Minimum detectable power near the quantum limit (about 10^{-20} watt for 1 Hz bandwidth) has been demonstrated [9,10]. Although results have been impressive, it is difficult to obtain IF bandwidths much larger than 1 GHz with such mixers. Moreover, they all require refrigeration, at least to 77° K. As one goes toward longer wavelengths, mixers are more difficult to make. A detectable power of 3×10^{-16} W at 119 μ using an extrinsic Si mixer and 2° K has bbeen reported [11]; in another experiment with an extrinsic GaAs mixer at 4° K, a detectable power of 10^{-14} watt was reported at 337 μ [12].

In principle, one should be able to do much better than this at wavelengths around 0.1 mm, using resistive diode mixers at room temperature. Minimum detectable powers on the order of kTB, or 4×10^{-21} watt/Hz, are theoretically possible. But results achieved to date fall short of theoretical limits: with Schottky diodes, for example, room-temperature detectable powers of 10^{-9}, 10^{-12}, and 5×10^{-15} W/Hz at 118, 170 and 337 microns, respectively [13,14]. One experiment has also been

done to test the metal-barrier-metal diode as a mixer [14] at 10 microns; the detectable power was 10^{-13} W/Hz at room temperature. This is the lowest value that has been obtained for 10-micron room-temperature detection, but it also far above theoretical limits.

With regard to room-temperature detection and mixing in the 1-3 mm range, conventional Schottky diodes have given good performance. However, there are difficulties with stability, ruggedness, and cost. Presently a new technology seems to be possible, based on the integration of dielectric waveguides and planar (or "surface oriented"") Schottky diodes, and perhaps other components into man-wave integrated circuits. Under other support we are presently studying devices for this purpose. Our work under JSEP relates to the principles and potential capabilities of such systems, especially as compared with the other types of receivers already mentioned.

In summary, progress in infrared/man detection and mixing in the coming years will involve (a) extension of the nearly quantum-limited sensitivities of superconductive devices as far as possible into the range above 100 GHz; (b) extension of the capabilities of room-temperature devices to wavelengths below one millimeter; and (c) development of efficient coupling schemes and rugged devices.

Progress and Publications Since Last Major Proposal

Work has continued on silicon membrane, sandwich-type superconductive devices which can be made either as Josephson junctions or super-Schottky diodes. These are being made with a two-step etching procedure. First, a membrane of about 50 x 50 μm^2 and 3 μm thick is made by preferential etching. The boron dopant used to stop the etching is then removed. A new, shallow doping is then done, and a small etch pit is made in the 3 μm thick layer. The final membrane is to be about 1 μm^2 with a thickness of 50 - 100 nm. The reason for using the two-step process is that it is necessary to know the thickness with greater precision than the allowed errors in the dimensions of the final membrane. We can measure the ≈3 μm-thick layer with some precision. We have had difficulty with spurious etching during the out-diffusion step and considerable effort has been devoted to developing an understanding of the process. Some improvements have been made in the yield. We have also taken the approach of doing the first etching step without a prior doping; the etching control is by timing and visual observation. The membranes thus formed do not have the damage which is a natural concommitant of the heavy doping for the thick membrane; we will seek to determine whether that changes the performance of the device. We have also developed a procedure for nondestructive measurement of the membrane thickness by using the penetration of the electron beam in a scanning electron microscope. We have started to develop a model for the semiconductor-barrier junction. A 90 GHz microwave mixing system has been prepared for testing the devices both as Josephson junctions and as super-Schottky diodes. This work is continuing.

Quasiparticle SIS mixers for the millimeter range are also being developed. Here our approach has centered on unifying the SIS junction with an antenna structure, the latter to provide efficient coupling. A typical design consists of a sandwich-type vee antenna with four SIS

junctions in series at its terminals. Performance approaching theoretical quantum limits is expected near 70 GHz. At higher frequencies, the capacitance of the junctions becomes a problem, and a novel method has been developed to tune reactance out. This method involves the use of an electrically adjustable reactance used to cancel this SIS junction's capacitance. The adjustable reactance is a large Josephson junction, dc biased below the critical current and connected across the SIS junctions with a length of superconducting transmission line. The latter is used to transform the adjustable reactance into the proper magnitude and phase for cancellation. With this scheme it should be possible to use the antenna-coupled SIS at frequencies up to 300 GHz.

In order to test [illegible] near this higher frequency, a 230 GHz isotopic methyl fluoride [illegible] constructed. The CO_2 pump laser for it is now working well [illegible] laser itself is being perfected.

This JSEP grant [illegible] exploratory research with planar Schottky diodes [illegible] these diodes has been developed and analyzed. Considered as detectors, these diodes are expected to have NEP higher [illegible] diodes by a factor of about ten. This drawback is [illegible] the greater ruggedness and integrability of the [illegible] practical development is now being carried on further [illegible].

We have shown that [illegible] coupling of radiation at 36 GHz into thin film metal-barrier-metal [illegible] can occur. Sensitivities within a factor of about three [illegible] of Schottky barrier junctions can be obtained for direct detection at 36 GHz. The noise was 1/f limited up to a few tens of megahertz when a bias was applied. The characteristics of this noise spectrum are attributable to impurity noise and can possibly be alleviated by better fabrication of the barrier material. In the absence of the 1/f spectrum (high frequency or zero bias), the noise was Johnston or shot in nature.

Heterodyne detection at 36 GHz and harmonic mixing using a 72 GHz signal were also performed. Conversion losses were respectively about ten to twenty db greater than that reported for commercially available detectors. However, [illegible] design for the harmonic mixing experiment was not used.

These experiments, the results of which are described in detail elsewhere [15], provide strong evidence that the metal-barrier-metal structure would be superior to Schottky barriers at higher frequencies: frequencies above which the spreading resistance results in inferior performance for the Schottky devices. We have thus initiated a study of the fundamental characteristics of metal-barrier-metal junction structures at shorter wavelengths.

An initial experiment [illegible] has demonstrated the coupling of 118 μm radiation to an [illegible] metal-barrier-metal structure situated at the center of an elevated [illegible] antenna. Although the sensitivity of detection was not high, the coupling principles first suggested by Hwang, et al. [17] were established for M-B-M junctions. The edge structure for the junction had an area of $\sim 10^{-10}$ cm^2 which is comparable to a point contact junction. Thus an RC time constant corresponded to a wavelength much shorter than 118 μm. This initial detection experiment established that coupling to planar junctions is possible and that fundamental investigations of a variety of mixing and detection experiments at shorter wavelengths are possible. This work is [illegible] continued.

Publications

The following papers acknowledged partial or total JSEP support:

(1) "Characteristics of Integrated MOM Junctions at D.C. and at Optical Frequencies," IEEE Jour. Quantum Elec., QE-14, 159 (1978).

(2) "Electronic Resonance of CARS," Phys. Rev., 18 (1978).

(3) "Photo-Induced Currents in Metal-Barrier-Metal Junctions," Radiation Energy Conversion in Space, ed. by K. W. Billman, 1978. (Vol. 61 of Progress in Astronautics and Aeronautics Series.)

(4) "Coupling to an Edge 'Metal-Oxide-Metal' Junction via an Evaporated Long Antenna," Appl. Phys. Lett., 34, 823 (1979).

(5) "Small Area Metal-Oxide-Metal Junctions as Picosecond Photoemissive Detectors," in Picosecond Phenomena, Springer Series in Chemical Physics, vol. 4 (edited by C. V. Shank, E. P. Ippen, and S. L. Shapiro).

(6) "Moving Toward NMM Wave Integrated Circuits," Microwave Journal, 47-52 (June 1980).

(7) "Progress in NMM Wave Integrated Circuits," to be presented at the Fifth International Conference on Infrared and Millimeter Waves, October 1980.

The following doctoral theses were completed by students receiving support from JSEP:

"Characteristics of Metal-Oxide-Metal Devices," Mordehai Heiblum. The abstract is as follows:

In the past ten years, metal-oxide-metal (MOM) devices, in their point-contact configuration, have been used for harmonic-, sum- and difference-generation at frequencies up to the near infrared, as well as for detection of visible radiation.

Because of the lack of mechanical stability of the point-contact configuration, planar MOM devices are desirable. Earlier efforts, however, have resulted in devices with undesirably large area. In this work I report a new integrated device with area comparable to that of the point-contact configuration ($\sim 10^{-10} cm^2$), which we name "Edge MOM." Fabrication methods and detection characteristics at DC and at 10.6, 3.39, and 0.6328 μm are described. A detailed description of the Edge MOM junction and its behavior under the influence of impinging radiation is given.

An extension of the MOM to an MOMOM is suggested in part two of the work. The suggested MOMOM has the theoretical capability of amplifying optical signals.

In order to find the limitations of the MOMOM, hot-electron devices such as: MOM-vacuum-metal, MOM-semiconductor, and MOMOM

are theoretically investigated. As a result a proposed structure with effective interaction area (10^{-10}–10^{-8})cm^2 and oxide thickness on the order of 10Å is proposed, which might have a transfer ratio of 0.3 - 0.5.

Different coupling mechanisms such as: wave-guiding, antenna, and surface-plasmon coupling are looked into and frequency limitations are estimated.

"Metal-Barrier-Metal Junctions for Millimeter Wave Mixing and Detection," Charles William Slayman. This thesis has the following abstract:

Metal-barrier-metal (MBM) junctions were used to mix and detect millimeter wave radiation. The MBM junctions used in this work were of the stable thin film type with areas of roughly 1 μm x 1 μm and fabricated using conventional photolithographic techniques. The devices tested were predominantly of the Ni-NiO-Ni variety.

A brief review of 1) the theory of the nonlinear current vs. voltage (I-V) characteristic of the MBM, 2) the equivalent circuit of the device, and 3) the processing steps used to fabricate the Ni-NiO-Ni junctions is presented. Devices of different impedances were produced by varying the processing procedure. The I-V characteristic, dynamic resistance R_{dyn}, and nonlinearity I"/I' were measured for the different devices. It was found that the nonlinearity was not dependent on the processing parameters. The low temperature (77K) characteristics of an Al-Al_2O_3-Ni and a Ni-NiO-Ni were measured. Between 4.2K and 77K, the I-V characteristic of the Ni-NiO-Ni junction did not change.

A brief introduction to the possible noise mechanisms in MBM junctions is presented. Any two terminal device (both of whose electrodes obey Fermi-Dirac statistics) that displays shot noise under bias will display shot noise at zero bias equivalent to the thermal noise of a resistor. This fact was experimentally observed in a 940Ω Ni-NiO-Ni junction. Under bias, however, the device displayed a $1/f^{1.1}$ noise spectrum up to 100 kHz and the RMS noise current was found to be proportional to the bias current and not the square root of the bias current.

Detection experiments were performed at 36 GHz with Ni-NiO-Ni junctions ranging from 180Ω to 12.3kΩ. The detected signal saturated at power levels above 10 μW. The millimeter wave response was studied under short pulse (60 ns) and long pulse (6 μs) conditions for a normal and a burned Ni-NiO-Ni device. The sensitivity of the junction was found to increase threefold at 77K. A comparison of the performance of the various Ni-NiO-Ni junctions to point contact MBMs and commercial Schottky detectors is made.

Fundamental mixing between two 36 GHz klystrons and harmonic mixing between a 36 GHz klystron and a 73 GHz klystron was performed using various Ni-NiO-Ni junctions. Mixer conversion loss and noise temperature were studied as a function of bias and local oscillator (LO) drive. Though the Ni-NiO-Ni diodes are not as sensitive as Schottky mixers and detectors, different MBM systems might ultimately prove to be more nonlinear.

Significant Accomplishments

We have gained an improved understanding of the processes involved in the fabrication, by the two-step etching procedure, of silicon membrane Josephson devices. Successful devices have been made and tested.

A new approach to tunable quasiparticle mixers has been devised. The novel features of this design are (a) use of an integral planar antenna to improve coupling and (b) use of an electrically-tunable variable reactance to cancel device capacitance.

The usefulness of metal-barrier-metal junctions as millimeter-wave mixers has been demonstrated experimentally. Results indicate that their mixer noise temperatures are comparable to those of Schottky diodes, although conversion is less.

References

(1) A. H. Silver, ed., 1976 Navy Study on Superconductive Electronics, August 2-13, 1976, Monterey, California, Office of Naval Research.

(2) A. R. Kerr, IEEE Trans. Microwave Theory and Techniques, MTT-23, 781, 1975.

(3) Y. Taur, J. H. Claassen, and P. L. Richards, IEEE Trans. Microwave Theory and Techniques, MTT-22, 1005, 1974.

(4) Y. Taur and A. R. Kerr, Appl. Phys. Lett., 32, 775, 1978.

(5) Y. Taur, to be published in IEEE Trans. on Electron Devices, ED-27, October 1980.

(6) J. R. Tucker, IEEE J. Quantum Electron., QE-15, 1234, 1979.

(7) M. McColl, M. F. Millea, A. H. Silver, M. F. Bottjer, R. J. Pederson, and F. L. Vernon, Jr., IEEE Trans. Magn., MAG-13, 221, 1977.

(8) P. L. Richards, to be published in IEEE Trans. Electron Devices, ED-27, October 1980.

(9) F. R. Arams, E. W. Sard, B. J. Peyton, and F. P. Face, IEEE J. Quantum Elect., QE-3, 484 (1967).

(10) C. J. Buczek and G. S. Picus, Appl. Phys. Lett., 11, 125, 1967.

(11) P. Norton, R. E. Slusher, and M. Sturge, reported at 2nd Int'l Conf. on Submillimeter Waves and Their Applications, San Juan, P.R., December 1967.

(12) T. DeGraauw, H. Van De Stadt, D. Bicanic, and B.Zuidberg, Infrared Physics, 16, 233, 1976.

(13) H. R. Fetterman, B. J. Clifton, P. E. Tannenwald, and C. D. Parker, Appl. Phys. Lett., 24, 70, 1974.

References, concluded

(14) H. R. Fetterman, B. J. Clifton, P. E. Tannenwald, C. D. Parker, and H. Penfield, IEEE Trans. Microwave Theory and Techniques, MTT-22, 1013, 1974.

(15) C. Slayman, "Metal-Barrier-Metal Junctions for Millimeter Wave Mixing and Detection," Ph.D. Thesis, University of California, Berkeley, CA (1980).

(16) Y. Yasuoka, M. Heiblum and T. K. Gustafson, Appl. Phys. Lett., 34, 823 (1979).

(17) T-L Hwang, D. B. Rutledge, and S. E. Schwarz, "Planar Sandwich Antennas for Submillimeter Applications," Appl. Phys. Lett., 34, 9 (1 January 1979).

(18) M. Heiblum, Ph.D. Thesis, University of California, Berkeley, CA (1978).

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: ISS-81-1 — Last Year's No.(s): ISS-80-1

Title: Large-Scale and Nonlinear Circuits Study

Senior Principal Investigator(s): L. O. Chua (415) 642-3209
E. S. Kuh 2-5771

Scientific Objective

Our objective is to continue our research efforts on large scale and nonlinear circuits which were initiated several years ago. The many tools and results that we have developed so far continue to serve as a foundation for our future research and will be used to attack several interrelated fundamental problems in this relatively unexplored but important area.

State of the Art

Network theory played a major role from the early 40's to the 60's in the development of the present day communication systems. The main thrust of network theory then was directed at the analysis and synthesis of linear circuits which can be characterized by a relatively small number of differential equations. Although in recent years many authors have published papers on nonlinear circuits and large-scale networks, the extent of the development of large-scale nonlinear circuits, both in theory and applications, is nowhere near the kind of maturity in classical network theory. The advances during the past decade in elecronic devices and integrated circuits, coupled with the immense impact of computers on circuit analysis and design, have drastically changed the nature of the problems faced by circuit theorists. While anlysis of circuits is still the key problem, it is more difficult in view of the size and complexity of the circuit and the inherent nonlinearity which exists in most electronic devices. Furthermore, the scope and significance of "circuit analysis" has been much broadened. Theory and techniques developed from large-scale networks and nonlinear circuit analysis can often be used in other types of large-scale network and system problems; for example, computer networks, power networks and complex control systems.

It should be noted that because of the size and complexity of LSI and VLSI, the objectives and approaches in analysis are considerably different from those of the classical network theory. First, computation becomes a key element in the study of any large circuit or system. The development of efficient algorithms is crucial. While theoretical results are essential, often one must also depend on heuristics. Second, the study of the structure of a large circuit and the property of interconnection is important. Frequently, large problems need to be divided into smaller sub-problems in order to facilitate analysis, data storage and computation. Third, design is usually accomplished by experience as a first step and improved on by repeated analysis. Fourth, such problems as reliability study, tolerance analysis, diagnosis and testing are important and should be kept in mind in the overall design process. The last item constitutes a new area of research which was not a part of classical network theory. All these indicate that there exist a large variety of problems of a circuit-theoretic nature which need to be studied.

Progress and Publications Since Last Major Proposal

The following is a summary of research progress in the area of nonlinear and large-scale networks which were published since the last major proposal.

1. Research Progress on Piecewise-Linear Analysis and Piecewise-Linear Algebra

Piecewise-linear techniques have been used extensively in circuits and systems theory to model dc nonlinear characteristics of electronic devices, and to study a large class of nonlinear resistive networks. In 1977, Chua and Kang introduced new analytical representations for one-dimensional piecewise-linear functions[1]. This piecewise-linear representation was subsequently generalized to the multi-dimensional case: it is applicable for any m-dimensional piecewise-linear function which is affine over convex polyhedral regions bounded by linear partitions[2]. This generalization results in a tremendous amount of data compression, thereby allowing large-scale piecewise-linear equations to be stored in significantly less computer memory space. Application of this result to the modeling and analysis of large-scale networks is presently under investigation.

Although motivated originally by analysis problems, the piecewise-linear representation in reference 2 led naturally to important applications in nonlinear circuit synthesis. In particular, systematic methods for synthesizing nonlinear networks having a prescribed scalar or multidimensional piecewise-linear function have been developed[3]. In the scalar case, precision active-circuit building blocks using operational amplifiers, transistors, diodes, and resistors have been derived for realizing piecewise-linear driving point and transfer characteristic plots. In the multidimensional case, methods have also been obtained for realizing a multiterminal nonlinear network having a multidimensional piecewise-linear transfer function. Moreover, these methods have been generalized by synthesizing nonlinear n-ports having a prescribed multidimensional piecewise-linear driving-point function. Although most of the basic building blocks are grounded active networks, converter networks have been developed for transforming such grounded networks into floating networks having the same properties. By slight modifications of these converter networks, other useful conversion properties have also been developed.

More recently, this multidimensional piecewise-linear representation has led to the partial resolution of a heretofore unsolved conjecture first posed in 1973[4]. In a recent paper[5],* we have proved that every reciprocal n-port resistor represented by our n-dimensional piecewise-linear function is realizable by a nonliner circuit containing only 2-terminal piecewise-linear resistors and a reciprocal linear element, such as a (p+q)-port transformer. This result thereby resolves one of the many fundamental questions raised in reference 6. In particular, we have proved the following:

---

*The second author (David J. Curtin) was supported by the JSEP Contract F44620-71-0087.

Theorem 1. n-port Reciprocity Criteria

A piecewise-linear n-port described by

$$i_1 = a_1 + b_1 v_1 + \ldots + b_{1n} v_n + \sum_{k=1}^{m_1} g_{1k}\left|\alpha_{1k_1} v_1 + \ldots + \alpha_{1k_n} v_n - \beta_{1k}\right|$$

$$\vdots$$

$$i_n = a_n + b_n v_1 + \ldots + b_{nn} v_n + \sum_{k=1}^{m_n} g_{nk}\left|\alpha_{nk_1} v_1 + \ldots + \alpha_{nk_n} v_n - \beta_{nk}\right|$$

is reciprocal if and only if

a) $b_{ji} = b_{ij}$

b) $m_j = m_i$

c) $\alpha_{jk_1} = \alpha_{ik_1}$, $k = 1,2,\ldots,m_j$

$$\vdots$$

$\alpha_{jk_n} = \alpha_{ik_n}$, $k = 1,2,\ldots,m_j$

$\beta_{jk} = \beta_{ik}$, $k = 1,2,\ldots,m_j$

Theorem 2. Reciprocal n-port Synthesis Criteria

A piecewise-linear n-port satisfying the above reciprocity criteria can be synthesized using only passive piecewise-linear 2-terminal resistors and a (p+q)-port transformer if and only if the set of algebraic conditions given in reference 5 satisfied.

Both theorems 1 and 2 could not be proved without using our multidimensional piecewise-linear representation whose explicit analytical representation was crucial in constructing the piecewise-linear algebraic proof.

2. Research Progress on Qualitative Nonlinear Network Analysis

Among the many important unsolved problems posed in the last major proposal concerning the foundation of nonlinear circuit theory, the following are some of the recent results published on this subject.

a. Implications of Capacitor-only Cutsets and Inductor-only Loops in Nonlinear Networks[7]

Let N be an autonomous dynamic nonlinear network. Let N_{RG} be the associated resistive subnetwork obtained by open circuiting all capacitors and short circuiting all inductors. We have proved the following results in reference 7.

(1) Suppose that N_{RG} has only isolated operating points. Then N has only isolated equilibria, if and only if, there are no capacitor-only cutsets and inductor-only loops.

(2) If the above condition is violated, then there are a continuum of equilibria even if the operating points are isolated.

(3) Let M be the set of equilibria. Then each trajectory is constrained to lie on an affine submanifold M^*, which depends on the initial state, such that $M \cap M^*$ has only isolated points. Hence, each trajectory behaves as if it has only isolated equilibria. The space M^*, because of its nature, can be considered as the minimal dynamic space of the network.

The above results are of special relevance to the computer simulation of nonlinear electronic circuits[8]. The presence of inductor-only loops and capacitor-only cutsets could lead to serious numerical problems during integration. These issues have been the subject of several heated debates[9,10] almost 20 years ago. The results presented in [7] provide a definitive and rigorous resolution of the fundamental issues raised in references 9 and 10.

b. Dynamics of Josephson-junction Circuits[11]

Although seemingly esoteric, the electromagnetic properties of Josephson junctions have been used in applications ranging from the measurement of minute computers with pico second switching times.

Although much has been published concerning Josephson-junction circuits, these articles are either quantum-mechanical analyses of the

Josephson effect or sundry reports of experiments which reveal some very remarkable phenomena associated with circuits containing Josephson junctions. Those who have ventured to solve the differential equations of Josephson-junction circuits have necessarily restricted themselves to approximate methods, or the use of approximate analog models. The situation remains somewhat unsatisfactory from the circuit theorist's point of view, as only a very limited insight is available into the general circuit behavior of the devices.

Our research on Josephson-junction circuits was conerned mainly with developing a unified qualitative theory of the phenomena associated with Josephson-junction circuits. Some recent progress has been reported[11]. In particular, the features of the d.c. I-V characteristic of a Josephson junction have been explained rigorously in terms of the flows on a cylindrical phase space. The junction phase difference ϕ attains an equilibrium point in the supercurrent regime, and acts like a current-controlled oscillator in the finite voltage regime. The hysteresis in these characteristics is due to the coexistence of an equilibrium point and a periodic solution.

For the a.c. excited Josephson junction, the dynamics are described for a simpler circuit model as trajectories on the surface of a torus. Using the concept of a turning point to define the various possibilities of periodic flows on the torus,, the character of harmonic and subharmonic oscillatory waveform has been derived. Furthermore, the existence of almost periodic waveforms has been established. The presence of constant-voltage steps is related to the structural stability of the turning point, which roughly means that the character of a periodic oscillation is not affected by small enough perturbations in the excitation. An algorithm is given in reference 11 to numerically determine the heights of these constant voltage steps.

A precise interpretation is also given in reference 11 showing how an a.c. excited junction is subject to synchronization phenomena, and that the step height is merely the entrainment range, or locking range, of each synchronization event. It is also shown how synchronization, in general, can be geometrically interpreted as closed trajectories on an integral manifold which can be smoothly transformed into an n-dimensional "torus."

Theory of Symmetry in Nonlinear Circuits [12,13]

Simple group-theoretic concepts have been used successfully in references 12 and 13 to develop a rigorous and comprehensive theory of symmetry for nonlinear elements and circuits. This theory does not rely on geometrical arguments or other ad hoc techniques normally invoked in such studies. This theory also unifies all forms of symmetry, including rotation, reflection and complementary symmetry into a single framework. It also includes all known nonlinear symmetry principles as special cases. Moreover, a general method for identifying all symmetry characteristics possessed by a nonlinear multiterminal element or circuit has been obtained. Some of the results that have been obtained concerning symmetry in a nonlinear element are:

(1) Several algorithms for synthesizing a nonlinear multiport or multiterminal element having any prescribed form of symmetry have been derived. In particular, various examples have been used to illustrate how these algorithms can be used to derive well-known symmetrical nonlinear circuit modules such as push-pull amplifiers, complementary-symmetric amplifiers, rectifiers, modulators, etc.

(2) A reduction algorithm has been developed which allows a complicated symmetric element to be analyzed by a much simpler reduced element.

(3) A general principle has been derived for applying symmetry to achieve frequency separation in nonlinear communication circuits where the even harmonic components are separated from the odd harmonic components.

Publications

(1) L. O. Chua and S. M. Kang, "Section-wise piecewise-linear functions: canonical representation, properties, and applications," Proc. IEEE, (Special Issue on Multidimensional Systems), vol. 65, pp. 915-929, June 1977.

(2) S. M. Kang and L. O. Chua, "A global representation of multidimensional piecewise-linear functions with linear partitions," IEEE Trans. on Circuits and Systems, vol. 25, pp. 938-940, Nov. 1978.

(3) L. O. Chua and S. Wong, "Synthesis of piecewise-linear networks," Electronic Circuits and Systems, vo. 2, pp. 102-108, July 1978.

(4) L. O. Chua, "Nonlinear circuit theory," Proc. 1978 European Conference on Circuit Theory and Design, vol. II, Guest Lectures, pp. 65-172, Lausanne, Switzerland, Sept. 4-8, 1978.

(5) L. O. Chua and F. J. Curtin, "Synthesis of reciprocal piecewise-linear n-port resistors," IEEE Trans. on Circuits and Systems, vol. [illegible], pp. 457-466, May 1980.

(6) J. L. Wyatt, Jr., L. O. Chua, and G. F. Oster, "Nonlinear n-port decomposition via the Laplace operator," IEEE Trans. on Circuits and Systems, vol. [illegible], pp. 741-754, Sept. 1978.

(7) T. Matsumoto, L. O. Chua and A. Makino, "On the implications of capacitor-only cutsets and inductor-only loops in nonlinear networks," IEEE Trans. on Circuits and Systems, vol. 26, pp. 828-845, Oct. 1979.

(8) L. O. Chua and P. M. Lin, Computer-Aided Analysis of Electronic Circuits: Algorithms and Computational Techniques, Prentice-Hall, Englewood Cliffs, N.J.

(9) A. Ivers, "The degrees of freedom in RLC networks," IRE Trans. Circuit Theory, vol. CT-6, pp. 91-95, March 1959.

(10) P. R. Bryant and A. Ivers, "The degrees of freedom in RLC networks," IRE Trans. Circuit Theory, vol. CT-7, pp. 173-174, June 1960.

Publications, concluded

(11) A. A. Abidi and L. O. Chua, "On the dynamics of Josephson-junction circuits," IEEE J. on Electronic Circuits and Systems, vol. 3, pp. 186-200, July 1979.

(12) L. O. Chua and J. Vandewalle, "A unified theory of symmetry for nonlinear multiport and multiterminal resistors," International Journal on Circuit Theory and Applications, vol. 7, pp. 337-371, 1979.

(13) J. Vandewalle and L. O. Chua, "A Unified theory of symmetry for nonlinear resistive networks," J. of the Franklin Institute, vol. 308, pp. 533-577, Dec. 1979.

Publications Under Combined and Other Sponsorship

(14) L. O. Chua and D. J. Curtin, "Synthesis of reciprocal piecewise-linear n-port resistors, IEEE Trans. on Circuits and Systems, vol. 27, pp. 367-380, May 1980.

(15) L. O. Chua and S. Wong, "Synthesis of piecewise-linear networks," Electronic Circuits and Systens, vol. 2, pp. 102-108, July 1978.

(16) A. A. Abidi and L. O. Chua, "On the dynamics of Josephson-junction circuits, IEE J. on Electronic Circuits and Systems, vol. 3, pp. 186-200, July 1979.

(17) T. Matsumoto, L. O. Chua and A. Makino, "On the implications of capacitor-only cutsets and inductor-only loops in nonlinear networks, IEEE Trans. on Circuits and Systems, vol. 26, pp. 828-845, Oct. 1979.

(18) J. Vandewalle and L. O. Chua, "A unified theory of symmetry for nonlinear resitive networks," J. of the Franklin Institute, vol. 308, pp. 533-577, Dec. 1979.

(19) L. O. Chua and J. Vandewalle, "A unified theory of symmetry for nonlinear multiport and multiterminal resistors," International Journal on Circuit Theory and Applications, vol. 7, pp. 337-371, 1979.

(20) L. O. Chua and C. Y. Ng, "Frequency-domain analysis of nonlinear systems: general theory," IEE J. on Electronic Circuits and Systems, vol. 3, pp. 165-185, July 1979.

(21) L. O. Chua and C. Y. Ng, "Frequency-domain analysis of nonlinear systems: formulation of transfer functions," IEE J. on Electronic Circuits and Systems, vol. 3, pp. 257-269, Nov. 1979.

(22) L. O. Chua, T. Matsumoto and S. Ichiraku, "Geometric properties of resistive nonlinear n-ports: transversality, structural stability, reciprocity, and anti-reciprocity," IEEE Trans. on Circuits and Systems, vol. 27, pp. 577-603, July 1980.

Interaction With Other Work Units

We anticipate interacting with the CAD efforts of Professors Polak and Sangiovanni-Vincentelli, as well as the large-scale system research of Professors C. A. Desoer, P.P. Varaiya, R. W. Brodersen et al. (Work units ISS-81-2 and SSD-81-4 respectively).

References

(1) S. W. Director and G. D. Hachtel, "Yield estimation using simplicial approximation," Proc. IEEE International Symp. on Circuits and Systems, 1977, pp. 579-582.

(2) S. W. Director and G. D. Hachtel, "The simplicial approximation approach to design centering and tolerance assignment," Proc. IEEE International Symp. on Circuits and Systems, 1976, pp. 706-709.

(3) L. O. Chua and P. N. Green, "Graph-theoretical properties of dynamic nonlinear networks," IEEE Trans. on Circuits and Systems, vol. CAS-23, no. 5, May 1976, pp. 292-312.

(4) L. O. Chua and D. N. Green, "A qualitative analysis of the behavior of dynamic nonlinear networks: stability of autonomous networks," IEEE Trans. on Circuits and Systems, vol. CAS-23, no. 6, June 1976, pp. 355-379.

(5) L. O. Chua and D. N. Green, "A qualitative analysis of the behavior of dynamic nonlinear networks: steady-state solutions of nonautonomous networks," IEEE Trans. on Circuits and Systems, vol. CAS-23, no.9, Sept. 1976, pp. 530-550.

(6) K. K. Clark and D. T. Hess, Communication Circuits: Analysis and Design, Addison-Wesley, Reading, Mass., 1971.

(7) L. O. Chua and P. M. Lin, Computer-aided Analysis of Electronic Circuits: Algorithms and Computational Techniques, Prentice-Hall, Englewood Cliffs, N.J., 1975.

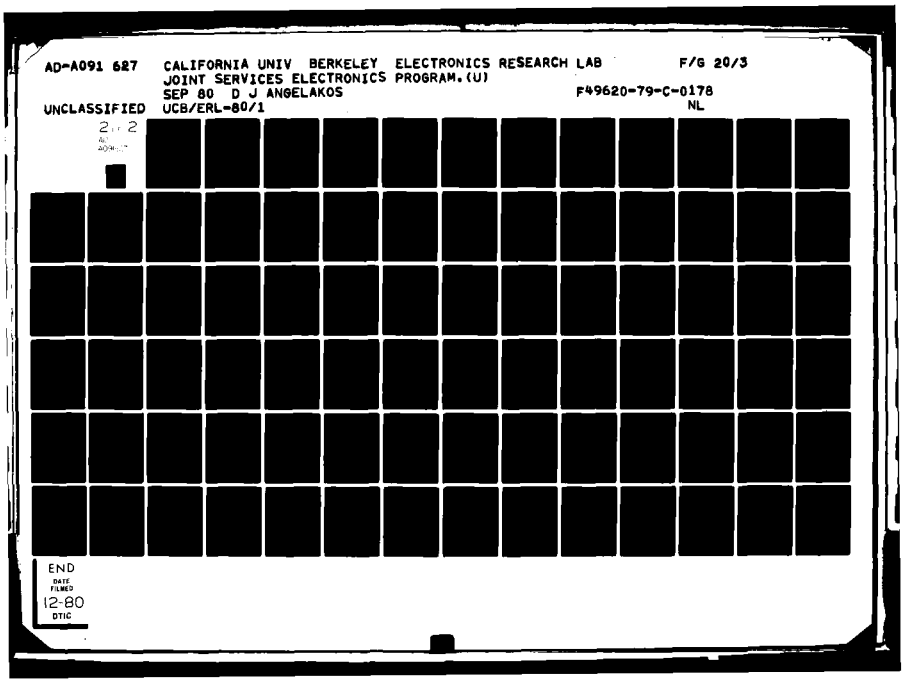
(8) N. Minorsky, Nonlinear Oscillations, Van Nostrand Company, Inc., New York, 1962.

(9) J. W. Graham and L. Ehrman (eds.), Nonlinear System Modeling and Analysis with Applications to Communications Receivers, Rome Air Development Center, Air Force System Command, RADC-TR-73-178, June 1973.

(10) L. A. Blackwell and K. L. Kotzebue, Semiconductor Diode Parametric Amplifiers, Prentice-Hall, Englewood Cliffs, N.J., 1961.

(11) M. J. Howes and D. V. Morgan, Microwave Devices, John Wiley and Sons, New York, 1976.

(12) L. O. Chua and S. M. Kang, "Section-wise piecewise-linear functions: canonical representation, properties, and applications, Proc. of the IEEE (Special Issue on Multidimensional Systems), vol. [illegible], no. 6, June 1977, pp. 915-929.


AD-A091 627 CALIFORNIA UNIV BERKELEY ELECTRONICS RESEARCH LAB F/G 20/3
JOINT SERVICES ELECTRONICS PROGRAM.(U)
SEP 80 D J ANGELAKOS F49620-79-C-0178
UNCLASSIFIED UCB/ERL-80/1 NL
2 OF 2
END
DATE FILMED
12-80
DTIC

University of California, Berkeley | Electronics Research Laboratory

Joint Services Electronics Program | September 30, 1980

Work Unit No.: ISS-81-2 | Last Year's No.(s): ISS-80-2

Title: Control of Large Systems

Senior Principal Investigator(s): C. A. Desoer (415) 642-0459
P. P. Varaiya 2-5270

Scientific Objective

The overall long term objective is to design control structures for unknown systems subject to random disturbances. The class of structures being investigated is the so-called "adaptive feedback control" laws, the unknown system is any countable state Markov chain whose unknown transition probabilities are parameterized. Also to be studied is the practically important case where the "real" system does not belong to the class of a priori selected models. In conjunction with this work, deterministic system design methods and evaluations are also investigated.

State of the Art

Over the past twenty-five years engineers have invented a variety of procedures for designing control strategies. The sophistication of these strategies has grown with the increase in the use of computers which enables the implementation of complicated strategies in real time (feedback control). But all these procedures rest on the assumption that the information available about the system and the calculation of the choice of control which is based on this information is centralized, that is it takes place in a single system.

As engineers began to consider the control of large systems* (e.g., power systems, communication networks) in a scientific manner, it became clear that "classical" procedures of design are inapplicable to the problem of Combinatorial Complexity. As the number of variables describing the system increases, the amount of computation necessary to apply classical control strategies grows even faster, soon exhausting the capability of existing and foreseeable computing capability. It was soon recognized that a way of dealing with this complexity is to insist on decentralized control strategies[1-4]. After this recognition, research has proceeded in three directions. First, there has been the attempt to derive design principles applicable to a fairly general class of decentralized controllers[5,6]. But this attempt was soon frustrated by a new difficulty, Informational Complexity**. As soon as information and control is decentralized, the information available and the effectiveness of the decision taken by each controller depend upon the decisions taken earlier by other controllers. This "simultaneity" reproduces the Combinatorial Complexity at another level and renders inapplicable existing techniques of controller design. The difficulties created by Informational Complexity are not well understood. On the one

---

*Systematic attention to the control of large systems began less than ten years ago. An indication of this is given by the fact that the IEEE Control Systems Society established its Technical Committee on Large Scale Systems in 1969, its first editorial on large systems appeared in 1974, and its first Special Issue on Large Systems in April 1978.

**We are indebted to Professor Y. C. Ho (personal communication) for his conceptualization of these two kinds of complexity.

hand we have several counterexamples of decentralized control problems which appear quite innocent, but whose optimal strategies are extremely complex[7,8,16]. On the other hand, we now know a (small) class of decentralized information structures for which optimal control strategies do have a simple structure[4].

The second direction of research has led to the search of optimum decentralized controllers for what have been called quasi-static control problems[9]. For these problems optimum controllers can have a simpler structure since only "steady state" behavior is of interest. Some very interesting solutions have already been proposed for the control of network flows[10] and for routing messages in a communication network[11].

Whereas the second direction described above seeks to reduce complexity by simplifying the control task (attention to steady state and ignoring transient behavior), the third direction reduces complexity by restricting a priori the structure of the class of decentralized controllers. In designing fixed structure controllers which guarantee adequate response against random disturbances, the attempts to date have been ad hoc [12-15]. It seems clear that considerable advance can be made if fixed structure decentralized controllers are investigated more systematically. This prediction is bolstered by the results recently obtained in the study of decentralized linear feedback controllers which guarantee adequate response against "deterministic but unknown" disturbances.

With the goal of designing robust controllers for large scale systems, the following approaches are relevant. First there is a very considerable literature on the stability of interconnected systems based on the Lyapunov method. In terms of generality of the results and of technical sophistication, the paper of Rasmussen and Michel deserves special mention[17]. Second, the problem can be approached from the input-output point of view: given the input-output properties of the subsystem and the topology of the interconnection, describe the I/O properties of the overall system. Under the joint sponsorship of NSF and JSEP we conducted a thorough investigation of this problem[18]. We refer the reader to its 46 item reference list. Recently we produced an improved formulation of the problem which led us to necessary and sufficient conditions for stability, even for the nonlinear case[37]. The goal of this research is to study the input-output properties of the overall system. The advantage of the approach, namely graphical decomposition, is that it applies equally to nonlinear time-varying just as well as linear time-invariant systems, either lumped or distributed. The graphical decomposition technique operates as follows: the digraph of the interconnected subsystem is decomposed into an acyclic interconnection of strongly connected components and then a minimal essential set is extracted to further simplify the analysis of the strongly connected components.

On the decentralized control of large systems, especially as it relates to tracking and disturbance rejection, the work of Davison[19,20] deserves special mention. We used it as well as graphical decomposition techniques to investigate the eigenvalue assignment and stabilization

problem of linear time-invariant interconnected systems[21]; one main result is that we can achieve eigenvalue assignment provided we operate at the column subsystem level, whereas if we restrict ourselves to summation node level, examples show that eigenvalue assignment cannot be achieved in general, whereas we prove that we can achieve stabilizatinon[21].

On the more specific topic of tracking and disturbance rejection, the considerable literature and several approaches used are reviewed in reference 22. Furthermore, the principal results are given a streamlined self-contained derivation in reference 23. Unfortunately, all this literature considers only linear, usually lumped systems and discusses robustness of the servocompensators only within that class[24]. The effect of nonlinear plant perturbation on optimal control design has recently been examined in references 25,26; in the broader aspect of I/O stability in references 27-29.

Only one recent report treats the tracking problem for nonlinear systems[30].

Adaptive control strategies are increasingly being suggested as an appropriate solution to the situation where the system to be controlled is not known and is subject to random disturbances. Adaptive control is a compromise between two extreme alternatives. The first: assume the unknown system is equal to a "nominal" system, may give a performance which is unacceptably degraded; the second: formulate the problem as a Bayesian decision problem and solve it by Dynamic Programming, while formally optimal, it cannot be "solved" except in the most trivial instances.

In adaptive control, one identifies the unknown system using previous data; and then uses the control assuming the current estimate of the unknown system to be the true system. As time progresses, and more data is collected, the uncertainty regarding the system declines and the performance improves. The crucial question is how fast this improvement in the knowledge and performance of the system occurs. Previous research has been primarily focused on linear systems.

References

(1) A. M. Geoffrion, "Elements of large-scale mathematical programming. Part I Concepts, Part II Systems of algorithms and bibliography," Management Science 16 (11), 652-691 (1970).

(2) P. Varaiya, "Trends in the theory of decision-making in large systems," Annals of Economic and Social Measurement 1, 493-499 (1972).

(3) M. Aoki, "On decentralized linear stochastic control problems with quadratic cost," IEEE Trans. Auto. Contr. AC-18, 243-250 (1973).

(4) Y. C. Ho and K. C. Chu, "Information structuress in dynamic multiperson teams," Automatica 10, 341-351 (1974).

(5) H. Witsenhausen, "Separation of estimation and control for discrete time systems," Proc. IEEE 59, 1557-1566 (1971).

(6) J. Marschak and R. Radner, The Economic Theory of Teams, Yale University Press, New Haven (1972).

(7) H. S. Witsenhausen, "A counterexample in stochastic optimum control, SIAM J. Control 6, 131-147 (1968).

(8) P. Varaiya and J. Walrand, "On delayed sharing patterns," Electronic Research Laboratory Memo M77-38, University of California, Berkeley (1977).

(9) P. Varaiya and L. Walrand, "Decentralized stochastic control," IFAC Workshop on Control and Management of Integrated Industrial Complexes, Toulouse, France (1977).

(10) R. Lau, R. M. Persiano and P. Varaiya, "Decentralized information and control: a network flow example," IEEE Trans. Auto. Contr. AC-17, 466-473 (1972).

(11) R. G. Gallager, "Local optimization of routing tables for data networks," Proc. 1976 IEEE Conf. on Decision and Control, 956-961 (1976).

(12) C. Y. Chong and M. Athans, "On the periodic coordination of linear stochastic systems," Proc. 6th IFAC World Congress, Boston, Mass., 1975.

(13) T. D. Linton, E. C. Tacker and C. W. Sanders, "Computational and performance aspects of static decentralized controllers," Proc. 1976 IEEE Conf. on Decision and Control, (1976).

(14) A. Benveniste, P. Bernhard and G. Cohen, "On the decomposition of stochastic control problems," Rapport de Recherche No. 187, IRIA, Rocquencourt, France (1976).

(15) N. R. Sandell, Jr., "Decomposition vs. decentralization in large-scale system theory," Proc. 1976 IEEE Conf. on Decision and Control (1976).

(16) I. B. Rhodes and D. G. Luenberger, "Stochastic differential games with constrained state estimation," IEEE Trans. Auto. Contr. AC-14, 476-481 (1969).

(17) R. D. Rasmussen and A. N. Michel, "Stability of interconnected dynamical systems described in Bansch spaces," IEEE Trans. Auto. Contr. AC-21, 4, 464-472 (1976).

(18) F. M. Callier, W. S. Chan and C. A. Desoer, "Input-output stability theory of interconnected systems using decomposition techniques," IEEE Trans. on Circuits and Systems, CAS-23, 12, 714- (1976).

(19) S. H. Wang and E. J. Davison, "On the stabilization of decentralized control systems," IEEE Trans. Auto. Contr. AC-18, 473-478 (1973).

(20) S. H. Wang and E. J. Davison, "A note on the simple modes of multivariable systems," IEEE Trans. Auto. Contr. AC-17, 548 (1972).

(21) W. S. Chan and C. A. Desoer, "Eigenvalue assignment and stabilization of interconnected systems using local feedback," submitted to IEEE Trans. Auto. Contr.

(22) Y. T. Wang, "Linear, time-invariant, lumped, multi-input multi-output servomechanism problems: tracking and disturbance rejection," M.S. Research Project, University of California, Berkeley, 1977.

(23) C. A. Desoer and Y. T. Wang, "The linear time-invariant servomechanism problem: a self-contained exposition," to appear in Advances in Control; also Electronics Research Laboratory Memo M77-50, University of California, Berkeley.

(24) See the detailed references of reference 23, and in particular, C. A. Desoer, F.M. Callier and W. S. Chan, "Robustness of stability conditions for linear time-invariant feedback systems," to appear in IEEE Trans. Auto. Contr., August 1977.

(25) M. G. Safonov and M. Athans, "Gain and phase margins for multi-loop LQG regulators," IEEE Trans. Auto. Contr. AC-22, 2, 173-179 (1977).

(26) P. K. Wong and M. Athans, "Closed-loop structural stability for linear quadratic optimal systems," Proc. 1976 IEEE Conf. on Decision and Control, 1231-1239 (1976).

(27) C. A. Desoer, "Plant perturbations in multivariable systems," J. Franklin Inst. 24, 4, 279-282 (1975).

(28) C. A. Desoer and M. Vidyasagar, Feedback systems: input-output properties, Academic Press (1975).

(29) D. Carluci and F. Donada, "Control of norm uncertain systems," IEEE Trans. Auto. Contr. AC-20, 792-795 (1975).

(30) W. M. Wonham, "On structurally stable nonlinear regulation with step inputs," System Control Report No. 7710, University of Toronto, July 1977.

Progress and Relevant Publications Since Last Major Proposal

A. Under Combined Sponsorship

1. Control of Markov Chain Models

The research reported here is jointly sponsred by NSF under Grant ENG79-03879. We have extended initial work[35] to propose a multi-layer structure for controlling large Markov chains[36]. The same ideas can be used to construct a finite chain model for a one-dimensional continuous diffusion[a]. Since the finite model is obtained from the continuous one by optional sampling, therefore at these sampling times the model is exact. This feature makes the model more attractive than the more usual grid approximations. However, our approach suffers from a major defect,

not present in other methods, in that it is limited at present to scalar processes. It is an important difficult task of future research to extend the results in [a] to the multidimensional case.

Adaptive control has become a major direction of research in control engineering. (One measure of its importance is the fact that six sessions of the 1980 JACC were devoted to it.) The bulk of the effort in adaptive control continues to be devoted to linear system models. However, our studies are directed to general Markov chain models. In our first set of results[b,c] we have essentially completely analyzed the case where it is assumed that the unknown system parameter belongs to an a priori specified finite set. In this case we have shown that (i) the parameter estimate converges in a finite random time and (ii) the estimate correctly identifies the closed loop transition probabilities but may not be able to identify the open loop transition probabilities. This result inspired Doshi and Shreve[d] to propose a randomization of the control policy, since such "noisy" input achieves open loop identifiability.

In [e,f] we have attempted to study the case where the state space of the chain is countable and where the unknown system parameter is in a compact set. The change from finite to the compact case creates difficulties. It is no longer possible to prove that the parameter estimate converges. Indeed, recently Kumar[g] has given an example where, with probability one, the estimate does not converge. However, the sequences of estimates always have certain (so-called "frequent") limit points where the closed-loop transition probabilities are correctly identified. Finally, two versions of randomized control policies are shown to achieve open loop identifiability.

2. Design of Deterministic Control Systems

Fundamental studies in nonlinear feedback systems have been completed: a general theory of multi-input multi-output nonlinear feedback systems has been completed and published[h]. It gives a complete generalization of the theory that H. S. Black presented for the linear time-invariant single-input single-output feedback system. In addition, it gives a completely general demonstration that the linearized inverse return difference is the quantity that controls the degree of desensitization to plant and/or output disturbances. It is also shown to play a key role in linearizing the I/O map of the closed-loop system.

The streamlining of the theory of the generalized Nyquist criterion and its generalization to the distributed case has been published[i]. We hear that the method has been programmed and is being used at TRW in Los Angeles. The features of our generalized Nyquist criterion is that (a) it applies to the distributed case, and (b) it does not require any reference to Riemann surfaces, branch cuts, etc. that previous derivations required.

An interesting approach to the study of linear feedback systems due to Zames has been adapted to the problem of designing multivariable feedback systems with stable plants. This design method is

revolutionary in that (a) it is based on the global parameterization of the four transfer functions pertaining to the problem, and (b) the stability of the design is easily checked without having recourse to such things as Nyquist diagrams etc. The design algorithm allows complete freedom - modulus, of course, the C_+ - zeros of the plant - in the choice of I/O map: therefore we can diagonalize the I/O map, assign zeros independently to each channel, assign poles independently to each channel and achieve tracking requirements. The simplest version of the algorithm was presented at the 1980 JACC[j], an extension of it will be presented at the 1980 CDC[k]. The first paper describing the algorithm has been accepted by the IEEE Trans. on Automatic Control. We are working out several extensions: one of our goals is to obtain a completely algebraic theory of design[l].

Many studies devoted to the effect of the plant perturbation on the stability of the system require that the perturbation be represented by stable operators. This is toally unrealistic in the case of an unstable plant: indeed, any perturbation in an unstable pole requires an unstable multiplicative perturbation[k,l].

B. Under NSF Exclusive Sponsorship

In NSF grant ENG78-09032 Desoer is investigating control problems for discrete-time[m] and continuous time[n] systems. Also, in[o], Desoer et al. demonstrated that the design algorithm developed under JSEP sponsorship did not impose unnecessary constraints on the choice of the I/O map. With a master's student, we are tying the design algorithm technique with Professor Polak's inequality constraint approach to design. Simple examples show that the method works and gives a rational technique for selecting parameters[p].

C. Significant Accomplishments

The spread of computer-assisted control has increased the possibility of implementing adaptive controllers which "tune" the control inputs to automatically detected changes in operating conditions. Considerably more work needs to be done, and this will take several years, before adaptive controllers can be implemented on a routine basis.

Work on statistical identification has shown us that it is possible to design experiments to identify an unknown system, and engineers have developed many methods for controlling a known system. The aim of adaptive control is to carry out both tasks - identification and control - concurrently. Our investigations, and the work of others, have proved that, in principle and under precisely stated conditions, this is indeed possible. Others have shown where adaptive controllers will operate satisfactorily for linear systems of the form:

$$\Sigma\, a_i y_{t-i} = \Sigma\, b_i u_{t-i} + \Sigma\, c_i w_{t-i}$$

where y_t, u_t, w_t are the output, input and white noise and the a_i, b_i, c_i are unknown parameters. Our work has resulted in conditions for the satisfactory control of systems of the form:

$$x_{t+1} = f(x_t, w_t, u_t, \text{theta})$$

where x_t is a discrete state, and theta is the unknown parameter.

A very exciting development in control system design occurred: by adapting a global parameterization of Zames, we have developed an algorithmic method of design that guarantees system stability, that quarantees a strictly proper controller and that can accomplish the following; (a) decouple the system, (b) assign the poles individually in each channel, (c) except for the C_+-zero imposed by the plant, assign the zeros in each channel, and (d) achieve tracking requirements. It is apparent that the technique is very general and applies to any algebraic system of a certain kind (e.g., continuous-time or discrete-time, lumped or distributed). The method lends itself naturally to interactive computer-aided design methodologies.

References

[a] V. Borkar and P. Varaiya, "Finite chain approximation to a continuous stochastic control problem," to appear in IEEE Trans. Automatic Control.

[b] _____, "Adaptive control of Markov chains," Int'l. Symposium on System Optimization and Anayisis, Lecture Notes in Control and Info. Sciences, No. 14, Berlin: Springer Verlag, 1979, 145-153

[c] _____, "Adaptive control of Markov chains, I: Finite parameter case," IEEE Trans. Automatic Control, AC-

[d] B. Doshi and S. Schreve, "Randomized self-tuning control of Markov chains," to appear in J. Applied Probability.

[e] V. Borkar and P. Varaiya, "Adaptive control of Markov chains," Joint Auto. Control Conference, August 1980, San Francisco, CA.

[f] _____, "Identification and control of Markov chains," to appear in SIAM J. Control and Optimization.

[g] P. R. Kumar, "Adaptive control with a compact parameter set," Math. Res. Report 80-16, Dept. of Math., University of Maryland, Baltimore County, July 1980.

[h] C. A. Desoer and Y. T. Wang, "Foundations of feedback theory for nonlinear dyanamical systems," IEEE Trans. Circuits and Systems, CAS-27, 2, pp. 104-123, 1980.

[i] C. A. Desoer and Y. T. Wang, "On the generalized Nyquist criterion," IEEE Trans. Circuits and Systems, CAS-25, 2, pp. 187-196, April 1980.

[j] C. A. Desoer and M. S. Chen, "Design of multivariable feedback systems with stable plants," 1980 JACC.

[k] C. A. Desoer and M. J. Chen, "Algebraic techniques in design and design evaluation," 1980 CDC.

[l] C. A. Desoer and M. J. Chen, "Work in progress."

[m] V. H. L. Cheng and C. A. Desoer, "General study of discrete-time convolution control systems," in preparation.

[n] F. M. Callier and C. A. Desoer, "Work in progress."

[o] V. H. L. Cheng and C. A. Desoer, "Limitations on the closed-loop transfer function due to right-half plane transmission zeros of the plant," accepted by IEEE Trans. Automatic Control.

[p] C. A. Desoer and C. L. Gustavson, "Work in progress."

Interaction with Other Units

We shall continue to interact with the research project of L. O. Chua and E. S. Kuh on nonlinear circuits and with E. Polak on computer optimization of electronic circuits.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: ISS-81-3 — Last Year's No.(s): ISS-80-3

Title: Computer Optimization of Electronic Circuits

Senior Principal Investigators(s):

R. G. Meyer	(415) 642-3306
E. Polak	2-2644
A. Sangiovanni-Vincentelli	2-4882

Scientific Objective

This project is a continuation of Project ISS-81-3, Computer Optimization of Electronic Circuits. Our chief objective remains the development of an interactive, optimization-based, computer-aided design methodology for the design of electronic circuits. To this end, we propose to continue developing specialized, dovetailing, single and multi-objective optimization algorithms, circuit simulation techniques and device models. In addition, since the development of progressively more complex systems makes sense only if these systems can be maintained, we propose to perform research on system diagnosability and fault analysis.

The optimization algorithms to be developed must be capable of solving complex, nondifferentiable, semi-infinite optimization and trade-off problems which arise in electronic circuit design when tolerances, trimming, and distributed constraints are taken into account. Our simulation procedures must be capable of producing not only circuit responses, but also the derivatives of these responses with respect to design parameters. In addition, they must have special variable precision features which result in a reduction of computing time at low precision, so that an optimization algorithm can call such a procedure with low precision when far from a solution and increase precision adaptively, as a solution is approached. The effect of such variable precision computation is to considerably reduce computing times. Since production tolerances can be imposed on only a very small number of device parameters, and since the optimization algorithms become extremely inefficient when tolerances on a large number of parameters are specified, device models must be developed in terms of production parameters by making use of the fact that the variation of many circuit parameters can be expressed in terms of variations of production parameters.

Finally, our theoretical work will be implemented and experimentally evaluated in an interactive-computer aided design facility which we are developing.

State of the Art

Optimization-based computer-aided design is certainly not a new phenomenon, see for example [B9,B11,B13,B15,B20,C1,K1,K2,P7,H16]. However, until quite recently, its use was severely limited by the fact that the available optimization algorithms were not able to solve design problems with tolerances, trimming and distributed constraints, such as those imposed on frequency or transient responses [B20]. The reason for this is that such a design problem frequently assumes the form

$$\min\{f(x) \mid g^i(x) \leq 0,\ i = 1,2,..,I;\ \max_{w\in W} h^j(x,w) \leq 0,\ j = 1,2,..,J;$$

$$\max_{e\in E}\ \max_{s\in S}\ \min_{t\in T}\ \max_{k\in K}\ z^k(x,e,s,t,) < 0\} \qquad (1)$$

where $g^i(.)$ represents simple constraints on the nominal design vector x, $h^j(.,.)$ represents nominal frequency (or time) dependent constraints on impedances or gains, etc., and z represents the requirement that performance be maintained in the presence of production errors e which can

Progress and Publications Since Last Major Proposal

A. Under JSEP

1. Professor A. Sangiovanni Vincentelli and E. Lelarasme, a graduate student, have developed a new inner approximations method for the design of electronic circuits. Their results were presented in the invited paper "An Inner Approximations Algorithm for the Design of Electronic Circuits," at the 1979 International Symposium on Mathematical Theory of Networks and Systems, Delft, Holland, July 3-6, 1979.

2. Professor A. Sangiovanni Vincentelli has developed, with N. B. Rabbat and H. Y. Hsieh of IBM, a new algorithm for the analysis of large scale nonlinear circuits in the time domain. Their results were reported in the paper "A Multi-level Newton Algorithm for the Analysis of Large Scale Nonlinear Circuits in the Time Domain," IEEE Trans. on Circuits and Systems, Special Issue on Computational Methods, September 1979.

3. Professor A. Sangiovanni Vincentelli has started a research effort in computer aided-design of power electronic circuits. The first results of this effort, co-authored with M. Venturini and P. Wood, "Models for Thyristors and Diodes in Digital simulation," was presented at the Power Elect. Specialists Conference, San Diego, June 18-23, 1979.

4. Professor A. Sangiovanni Vincentelli and V. Visvanathan, a graduate student, have developed a theory for the fault diagnosis of nonlinear memoryless systems and a technique for the design of diagnosable systems. Their work was reported in "DC Testing of Parametric Faults in Nonlinear Systems," IEEE International Symposium on Circuits and Systems, Houston, Texas, April 28-30, 1980.

5. Professor A. Sangiovani Vincentelli and E. Lelarasme, a graduate student, have submitted the paper "Time Domain Sensitivity Analysis by the Perturbation Method," to IEEE Trans. on Circuits and Systems.

6. Professors E. Polak, A. Sangiovanni Vincentelli, et al, have described our interactive optimization software system in "A Software for Optimization-Based Computer-Aided Design," IEEE International Symposium on Circuits and Systems, Houston, Texas, April 28-30, 1980.

7. Professors E. Polak, A. Sangiovanni Vincentelli and D. Q. Mayne have made a considerable amount of progress in developing algorithms for design centering, tolerancing and tuning. An important breakthrough was presented by Polak and Sangiovanni Vincentelli in "Theoretical Aspects of the Optimal Design Centering, Tolerancing and Tuning Problems," 4th Intl. Symp. on Math. Theory of Networks and Systems, Delft University of Technology, Holland, July 3-6, 1979, and in "Theoretical and Computational Aspects of the Optimal Design Centering, Tolerancing and Tuning Problem," IEEE Trans. on Circuits and Systems, Vol. CAS-26, No. 9, 1979. A considerable improvement on this method is developed by Polak in "An Implementable Algorithm for the Optimal Design Centering, Tolerancing and Tuning Problem," presented at the IFIA International Symposium on

be counteracted by adjusting the trimming parameters t. The variable s may represent time or frequency or temperature, etc. The above problem is easily recognized as a non-differentiable, semi-infinite optimization problem, i.e., about as difficult an optimization problem as one cares to think of.

Although there is a fairly large literature on algorithms for various classes of semi-infinite and nondifferentiable optimization problems, see e.g., [B25,B26,B27,D8,D9,G6,G7,G8,H12,M10,P14,P16,P17a,H1,T1], we find that many of these algorithms are either conceptual (i.e., involve operations that one is not able to perform) or address themselves to very restrictive classes of problems, such as those with one-dimensionally convex constraint sets [B9,B11,B13,B15]. As far as general purpose, implementable algorithms are concerned, there appear to be only three [P14,G6,T1] which solve the simpler case of (1) when there are no tolerance and trimming constraints present, two [G6,P4] which allow for tolerances and only one [P5] which solves (1) in its complete generality. All of these three algorithms were co-authored by E. Polak.

In addition to the difficulties mentioned above, the use of optimization techniques in electronic circuit design was, and still is, severely handicapped by the fact that existing simulation codes, e.g. the ones described in [K1,J6,Z2], which must be called for function and derivative evaluation, have inadequate provisions for derivative calculations. For example, if we consider a sample of the best known computer aided analysis programs, such as ASTAP [A6], CIRCUS [D7], ECAP [E2], NET 2 [M7], SCEPTRE [B61], SUPERSCEPTRE [S12], SPICE 2 [N3] and BELAC [G12], we find, quite typically, that ASTAP computes no sensitivities, SPICE 2 computes only small-signal sensitivities, and none of them compute temperature sensitivity. We are now beginning to develop an effort to extend these programs so that required derivatives will also be computed. In addition to the simulation programs mentioned above, programs based on tearing algorithms [B28,C9,H5,H6,K8,M14,R1,S3-S8,S10,S11,W5], and on model approximation and decoupling [C6,F1] are also being considered for extension since they are more efficient in large-system applications.

As specialized optimization algorithms began to be developed for electronic circuit design, such as [P4,P5], it became obvious that existing device models were completely incompatible with the need of keeping the total number of toleranced variables small. Quite recently R. G. Meyer was able to show that more suitable models can be developed, because many of the important variables are correlated, and that their behavior can be expressed in terms of a reasonably small number of variables the tolerances on which can be controlled in the production process, such as sheet thickness, resistivity, device scaling factors, epitaxial doping, etc.

As far as fault diagnosis is concerned, we find theoretical results for the diagnosability of linear circuits and systems [B1,B3,B4,E3,L1,N1,R2,R3,S1,S2,S11,T1,T4-T6]. Some preliminary results for the diagnosability of memoryless nonlinear circuits and systems were co-authored by A. Sangiovanni Vincentelli [S12]. However, there appear to be no diagnosability results for dynamic nonlinear circuits and systems.

Numerical Methods in Engineering, Versailles, France, December 10-15, 1979, and also to appear in JOTA. Mayne, Polak and Voreadis will present the paper "A Cut Map Algorithm for Design Problems with Parameter Tolerances" at the 19th IEEE Conference on Decision and Control, Albuquerque, N.M., December 10-12, 1980. This is a highly efficient algorithm for use when only feasibility and not optimality need to be obtained. Finally, Mayne, Polak and Sangiovanni-Vincentelli have summarized their work in the survey paper "Computer Aided Design via Optimization" which was presented at the IFAC Workshop on Control Applications of Nonlinear Programming, Denver, Co., August 1979. This This paper has also been provisionally accepted by Automatica.

8. Professor E. Polak and A. N. Payne, a graduate student, have developed an optimal process for multi-objective decision making. Their work was reported in the paper "An Interactive Rectangle Elimination Method for Bi-objective Decision Making", IEEE Trans. on Control, vol. AC-25, No. 3, 1980.

9. Professor E. Polak presented an invited paper "On the Nature of Optimization Problems in Engineering Design" at the 10th International Symposium on Mathematical Programming, Montreal, Canada, August 27-31, 1979.

10. Professors E. Polak and D. Q. Mayne have developed two superlinearly convergent algorithms for constrained optimization problems. The first is of the secant type and is described in "A Robust Secant Method for Optimization Problems with Inequality Constraints," to appear in JOTA. The second one is of the recursive quadratic programming type, with an automatic feature for setting the exact penalty function, is described in "A Superlinearly Convergent Algorithm for Constrained Optimization Problems" at the 10th International Symposium on Mathematical Programming, Montreal, Canada, August 27-31, 1979. This paper is also under consideration for inclusion in a Mathematical Programming Studies volume.

11. Professors E. Polak and D. Q. Mayne have developed several methods for the solution of nonlinear inequalities in a finite number of iterations. Their work is reported in "On the Finite Solution of Nonlinear Inequalities", IEEE Trans. on Automatic Control, vol. AC-24, No. 3, 1979, with A. J. Heunis, in "Solving Nonlinear Inequalities in a Finite Number of Iterations", to appear in JOTA; and in "Algorithms for the Design of Control Systems by the Method of Inequalities" and in "A Quadratically Convergent Algorithm for Solving Infinite Dimensional Inequalities", both presented at the 18th IEEE Conference on Decision and Control, Fort Lauderdale, Florida, December 12-14, 1979.

12. Professor E. Polak and Dr. C. Gonzaga have developed a special outer approximations theory for computer-aided engineering design. Their work is reported in "On Constraint Dropping Schemes and Optimality Functions for a Class of Outer Approximations Algorithms," SIAM J. Control and Optimization, vol. 17, No. 4, 1979.

13. Professor E. Polak and A. Tits, a graduate student, have developed

a new multiplier method which is described in "A Globally Convergent Multiplier Method with Automatic Penalty Limitation," to appear in Journal of Applied Mathematics and Optimization.

14. Professor A. Sangiovanni Vincentelli and his students have been testing some of our new optimization algorithms to determine if they can be used to improve significantly on a competent design. In the case of a wide-band amplifier, designed by Prof. R. G. Meyer, they have found that they could increase the bandwidth from 900 MHz to 1300 MHz while meeting input impedance, output impedance, insertion gain, and reflection coefficient constraints. This is a very significant improvement which shows that our optimization algorithms are well suited to electronic circuit design.

15. In the past, optimization with tolerancing of practical electronic circuits, has been seriously limited by the number of variables involved. For example, a reasonably accurate model of a bipolar transistor or MOS device requires at least 8 parameter values for its specification. These parameters parameters are all functions of bias conditions, temperature and process variation. Since the smallest subcircuit for which optimization can be usefully employed will typically contain ten or twenty components, the number of variables becomes prohibitive.

Prof. R. G. Meyer's initial effort in the area of modelling for optimization has been directed towards reducing the number of variables required, while still maintaining model accuracy. Initial work has been directed towards bipolar integrated-circuit technology, where a new modelling scheme has been developed. This allows the modelling of arbitarily large circuits using only four basic process parameters to represent the effect of process tolerances. This advance has been made possible by recognition of the excellent tracking characteristics which are inherent in modern integrated-circuit technology together with a close attention to the capabilities and requirements of the optimization algorithms being developed by our research team. Using these models, realistic optimization of complex circuits, including tolerancing, is now possible.

Significant Accomplishments

The significant accomplishments of our research can be summarized as follows:

1. We have developed a prototype interactive, optimization based computer aided design package, capable of accepting semi-infinite constraints on frequency and time responses, but not tolerancing or post manufacturing tuning. This package serves as a test bed for the development of ideas and concepts for a much more sophisticated package which is now being constructed.

2. We have shown that device models can be obtained which make it practical to solve the optimal design centering, tolerancing and tuning problem.

3. We have developed a number of optimization and inequality solving algorithms for computer aided design which either solve problems that were hetherto unsolvable, or which converge much more rapidly than currently available algorithms.

4. We have obtained a number of important results in circuit and system fault diagnosis.

References

A6 ASTAP General Information Manual (GH20-1271-0), IBM Corp., Mechanicsburg, PA.

B1 R. S. Berkowitz, IRE Trans. on Circuit Theory, vol. CT-9, pp. 24-29, March 1962.

B2 M. L. Balinski and P. Wolfe, (eds.), Nondifferentiable Optimization, Math. Prog. Study 3, Amsterdam: North-Holland, 1975.

B3 S. D. Bedrosian and R. S. Berkowitz, IRE International Convention Record, Part 2, pp. 16-24, March 1962.

B4 S. D. Bedrosian, IEEE Trans. on Communication and Electronics, pp. 219-224, March 1964.

B9 J. W. Bandler and P. C. Liu, IEEE Trans. on Circuits and Systems, pp. 219-222, March 1974.

B11 J. W. Bandler, J. of Optimization Theory and Applications, vol. 14, no. 1, pp. 99-114, July 1974.

B13 J. W. Bandler, P. C. Liu, and J. H. Chen, IEEE Trans. on Microwave Theory and Techniques, vol. MTT-23, no. 8, pp. 630-641, August 1975.

B14 J. Bowers and S. Sedone, SCEPTRE: A Computer Program for Circuit and System Analysis, Englewood Cliffs, N.J.: Prentice Hall, Inc., 1971.

B15 J. W. Bandler, P. C. Liu, and H. Troup, IEEE Trans. on Circuits and Systems, vol. CAS-23, no. 3, pp. 155-165, March 1976.

B20 S. V. Bearse, Microwaves Journal, June 1977.

B23 D. P. Bertsekas and S. K. Mitter, SIAM J. Control, vol. 11, no. 4, pp. 637-652, November 1973.

B24 D. P. Bertsekas, Nondifferentiable Optimization Via Approximation, Math. Prog. Study 3, pp. 1-25, Amsterdam: North-Holland, 1975.

B25 J. W. Blankenship and J. E. Falk, "Infinitely Constrained Optimization Problems," The George Washington University Institute for Management Science and Engineering, Serial T-301, June 174.

B26 J. Bracken and J. F. McGill, Operations Res. 21, pp. 37-44, 1973.

B27 J. Bracken and J. F. McGill, Operations Res. 22, pp. 1097-1101, 1974.

B28 F. H. Branin, The Matrix and Tensor Quarterly, vol. 12, no. 3, pp. 69-115, March 1962.

B41 USAF Technical Report AFWL-TR-73-75, Air Force Weapons Laboratory, Kirkland AFB, N.M., 1973.

C1 D. A. Calahan, Computer-Aided Network Design, New York: McGraw-Hill, 1968.

C6 B. R. Chawla, H. K. Gummel, and P. Kozak, IEEE Trans. on Circuits and Systems, vol. CAS-22, no. 12, December 1975.

C9 L. O. Chua and L. K. Chen, IEEE Trans. on Circuits and Systems, vol. CAS-23, no. 12, pp. 694-705, December 1976.

C10 J. L. Cochrane and M. Zeleny, (eds.), Multiple Criteria Decision Making, Columbia, S.C.: USC Press, 1973.

D2 N. O. Da Cunha and E. Polak, "Constrained Minimization Under Vector-Valued Criteria in Linear Topological Spaces," in A. V. Balakrishnan and L. W. Neustadt, (eds.), Mathematical Theory of Control, New York: Academic Press, pp. 96-108, 1967.

D3 J. M. Danskin, The Theory of Max-Min, Springer-Verlag, Berlin, 1967.

D7 B. Dembart and L. Milliman, "CIRCUS-2, A Digital Computer Program for Transient Analysis of Electronic Circuits," Harry Diamond Laboratories, Washington, D.C., July 1971.

D8 V. F. Demjanov, J. Computer and System Sciences 2, pp. 342-380, 1968.

D9 V. F. Demjanov, Kybernetics 2, no. 6, pp. 58-66, 1966; 3, no. 3, pp. 62-66, 1967.

D13 S. W. Director and R. A. Rohrer, IEEE Trans. on Circuit Theory, pp. 318-323, August 1969.

D16 S. W. Director and G. D. Hachtel, Proc. IEEE 1976 ISCAS, pp. 706-709.

E1 B. Curtis Eaves and W. I. Zangwill, SIAM J. of Control, vol. 9, no. 4, pp. 529-542, November 1971.

E2 ECAP II Application Description Manual (GH20-0983), IBM Corp., Mechanicsburg, PA.

E3 S. Even and A. Lempel, IEEE Trans. on Circuit Theory, vol. CT-14, pp. 361-364, September 1967.

F1 S. P. Fan, M. Y. Hsueh, A. R. Newton, and D. O. Pederson, Proc. IEEE ISCAS, 1977.

G6 C. Gonzaga and E. Polak, SIAM J. Control and Opt., 1977.

G7 C. Gonzaga, E. Polak, and R. Trahan, IEEE Trans. Automatic Control, vol. 25, no. 1, p. 49, 1979.

G8 Gustafson and Kortanek, Naval Research Logistics Quarterly, vol. 20, pp. 477-504, 1973.

G12 C. A. George, BELAC User's Manual, Technical Information Service R69 EMLII, General Electric Co., Utica, N.Y., 1969; also updated R72 ELI, 1972.

H1 R. Hettich, (ed.), Semi-Infinite Programming, Proceedings of a Workshop, Bad Honnef, August 30 - September 1, 1978.

H2 G. D. Hachtel, R. K. Brayton, and F. G. Gustavson, IEEE Trans. on Circuit Theory, vol. CT-18, pp. 101-118, January 1971.

H5 H. H. Happ, Diakoptics and Networks, New York: Academic Press, 1971.

H6 H. H. Happ, Proc. IEEE, vol. 62, pp. 930-940, July 1974.

H10 C. W. Ho, A. E. Ruehli, and P. A. Brennan, IEEE Trans. on Circuits and Systems, vol. CAS-22, pp. 504-508, June 1975.

H12 W. W. Hogan, Mathematical Programming 5, 2, pp. 151-168, 1973.

H14 H. Y. Hsieh and N. B. Rabbat, Proc. IEEE ISCAS, 1977.

H16 Computer-Aided Integrated Circuit Design, G. J. Herskowitz (ed.), McGraw-Hill, New York, 1968.

I2 IEEE Transaction on Microwave Theory and Techniques (Special Issue on Computer-Oriented Microwave Practices), pp. 416-634, August 1969.

I3 IEEE Transactions on Circuit Theory (Special Issue on CAD), pp. 3-173, January 1971.

I4 IEEE J. Solid-State Circuits (Special Issue on Computer-Aided Circuit Analysis and Device Modeling), pp. 146-259, August 1971.

I5 IEEE Transactions on Circuit Theory (Special Issue on CAD), November 1973.

J6 Handbook of Circuit Analysis Languages and Techniques, R. W. Jensen and L. P. McNamee (eds.), Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1976.

K1 G. Kaplan, "Computer-Aided Design," IEEE Spectrum, October 1975.

K2 M. J. Kelly, "CAD Limits LSI," Proc. VIII Asilomar Conference, December 1974.

K5 R. Klessig and E. Polak, SIAM J. Control, vol. 11, no. 1, pp. 80-83, February 1973.

K6 R. Klessig and E. Polak, J. Math. Anal. and Appl., vol. 41, no. 3, pp. 583-602, March 1973.

K7 R. Klessig and E. Polak, "A Survey of Convergence Theorems," invited paper, Joint National Meeting, ORSA-TIMS, 17-19, November 1975, Las Vegas, Nevada.

K8 G. Kron, Diakoptics-Piecewise Solution of Large-Scale Systems, London, England: MacDonald, 1963.

K9 Computer Oriented Circuit Design, F. F. Kuo and W. G. Magnuson, Jr. (eds.), Englewood Cliffs, N.J.: Prentice-Hall, 1969.

L1 R. Liu and V. Visvanathan, IEEE Trans. on Circuits and Systems, vol. CAS-26, no. 7, pp. 490-496 and pp. 558-564, July 1979.

L4 C. Lemarechal, "An Algorithm for Minimizing Convex Functions," Proc. IFIP Congress 74, August 1974.

L5 C. Lemarechal, in Nondifferentiable Optimization, Math. Prog. Study 3, pp. 95-109, M. L. Balinski and P. Wolfe, (eds.), Amsterdam: North-Holland, 1975.

L6 C. Lemarechal, "Minimization of Nondifferentiable Functions with

Contraints," Proc. Allerton Conference, October 2, 1974.

L9 E. S. Levitin and B. T. Polyak, Zh. Vychisl. Mat. Mat. Fiz., 6, 5, pp. 787-823, 1966.

L10 E. S. Levitin, Zh. Vychisl. Mat. Mat. Fiz., 9, 5, pp. 783-806, 1969.

M1 K. R. MacCrimmon, "An Overview of Multiple Objective Decision Making," in J. L. Cochrane and M. Zeleny (eds.), Multiple Criteria Decision Making, Columbia, S.C.: USC Press, pp. 18-44, 1973.

M7 NET-2 Network Analysis Program, Harry Diamond Laboratories, Washington, D.C., 1970.

M9a D. Q. Mayne and E. Polak, JOTA, vol. 10, nos. 3/4, pp. 277-300, August 1975.

M9b D. Q. Mayne and E. Polak, "An Exact Penalty Function Algorithm for Optimal Control Problems with Control and Terminal Equality Constraints," in press.

M9c D. Q. Mayne and E. Polak, Math. Programming, vol. 11, pp. 67-80, 1976; also ERL Memorandum No. M-457, University of California, Berkeley, August 2, 1974.

M10 D. Q. Mayne, E. Polak, and R. Trahan, ERL Memorandum M77/10, University of California, Berkeley, February 8, 1977.

M15 R. G. Meyer, R. A. Rohrer, L. W. Nagel, and L. Weber, IEEE J. Solid-State Circuits, vol. SC-6, no. 4, pp. 204-213, August 1971.

M16 R. G. Meyer and D. M. Miller, IEEE J. Solid-State Circuits, vol. SC-6, no. 4, pp. 244-250, August 1971.

M17 R. G. Meyer, R. Rohrer, L. W. Nagel, and L. Weber, IEEE ISSCC Digest, vol. 14, pp. 124-125, 1971.

M18 R. G. Meyer, M. J. Shensa, and R. Eschenbach, IEEE J. Solid-State Circuits, vol. SC-7, no. 1, pp. 16-23, February 1972.

M19 R. G. Meyer and W. M. Sansen, IEEE J. Solid-State Circuits, vol. SC-7, no. 6, pp. 492-498, December 1972.

M20 R. G. Meyer, L. Nagel, and S. Lui, IEEE J. Solid-State Circuits, vol. SC-8, no. 3, pp. 237-240, June 1973.

M21 R. G. Meyer and H. Abraham, IEEE Trans. Electron Devices, vol. ED-23, No. 12, pp. 1290-1297, December 1976.

M22 R. G. Meyer and D. G. Duff, IEEE ISCAS Proc., pp. 19-22, 1977.

M23 R. G. Meyer and K. H. Chan, IEEE ISSCC Digest, vol. 20, pp. 208-209, 1977.

M24 R. Mifflin, Report RR-76-21, International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria, December 1976.

M27 H. Mukai and E. Polak, "On the Implementation of Reduced Gradient Methods," 7th IFIP Conf. on Optimization Techniques, Nice, France, September 8-13, 1975; also in Optimization Techniques Modeling and Optimization in the Service of Man, vol. 2, pp. 426-437, Berlin, New York: Springer-Verlag, 1976

M28 H. Mukai and E. Polak, ERL Memorandum M-561, University of California, Berkeley, July 2, 1975; also JOTA, in press.

M29 H. Mukai and E. Polak, ERL Memorandum M-562, University of California, Berkeley, August 14, 1975; also Math. Prog., in press.

N1 N. Navid and A. N. Willson, IEEE Trans. on Circuits and Systems, vol. CAS-26, no. 7, pp. 440-457, July 1979.

N3 L. W. Nagel, ERL Memorandum M-520, University of California, Berkeley, May 1975.

P3 H. J. Payne, E. Polak, D. C. Collins, and W. S. Meisel, IEEE Trans. Automat. Contr., vol. AC-20, pp. 546-548, August 1975.

P4 E. Polak, "Algorithms for a Class of Computer-Aided Design Problems: A Review," Automatica, September 1979.

P5 E. Polak, "An Implementable Algorithm for the Optimal Design Centering, Tuning, and Tolerancing Problem," presented at IRIA International Symposium on Numerical Methods in Engineering

P6 E. Polak and A. Sangiovanni-Vincentelli, "Theoretical Aspects of the Optimal Design Centering, Tolerancing, and Tuning Problems," IEEE International Symposium on Circuits and Systems, Delft University of Technology, Holland, July 3-6, 1979.

P7 J. F. Pinel, F. Brglez, W. Chu, and O. Monkewich, Proc. IEEE 1976 ISCAS.

P8 H. J. Payne and E. Polak, IEEE Trans. on Automatic Control, vol. AC-25, No. 3, 1980.

P8a A. N. Payne, "Internal Elimination Methods for Interactive Optimization of Multiple Objectives," University of California, Berkeley, May 1979.

P9a E. Polak, Computational Methods in Optimization - A Unified Approach, Academic Press, N.Y., 1971.

P9b E. Polak, "Computational Methods in Optimal Control," invited paper, Conf. on Energy Related Modelling and Data Base Management, Brookhaven National Labs., May 12-14, 1975.

[P9c] E. Polak, Automatic, vol. 12, pp. 337-342, 1976.

[P9d] E. Polak, "Optimization Algorithms for Computer Aided Design," Plenary Address Optimization Days-1977, sponsored by IEEE Control Systems Society SIAM, May 5-6, 1977, Concordia University, Montreal, Quebec.

[P10] E. Polak, "On a Class of Numerical Methods with an Adaptive Integration Subprocedure for Optimal Control Problems," in Techniques of Optimization, A. V. Balakrishnan, (ed.), Academic Press, 1972, pp. 89-103.

[P11] E. Polak, "On the Approximation of Solutions to Multiple Criteria Decision Making Problems," presented at XXII International Meeting of the Institute of Management Sciences, Kyoto, Japan, July 24-26, 1975; also in M. Zeleny (ed.), Multiple Criteria Decision Making: Kyoto, 1975, Berlin: Springer-Verlag, 1976, pp. 271-282.

[P12a] E. Polak and D. Q. Mayne, JOTA, vol. 16, nos. 3/4, pp. 303-325, August 1975.

[P12b] E. Polak and D. Q. Mayne, IEEE Trans. Automat. Contr., vol. AC-22, no. 5, 1977.

[P13] E. Polak and A. N. Payne, "On Multicriteria Optimization," in Y. C. Ho and S. K. Mitter (eds.), Directions in Large-Scale Systems, New York: Plenum Publishing Corporation, pp. 77-94, 1976.

[P14] E. Polak and D. Q. Mayne, IEEE Trans. on Automat. Contr., vol. AC-21, no. 2, pp. 184-193, April 1976.

[P15] E. Polak, K. S. Pister, and D. Ray, Engineering Optimization, vol. 2, pp. 65-71, 1976.

[P16] E. Polak and R. Trahan, "An Algorithm for Computer Aided Design Problems," Proc. of the 1976 IEEE Conf. on Decision and Control, December 1976.

[P17] E. Polak, R. Trahan, and D. Q. Mayne, ERL Memorandum M77/39, University of California, Berkeley, May 31, 1977.

[P17a] E. Polak, D. Q. Mayne, and R. Trahan, "An Outer Approximation Algorithm for Computer-Aided Design Problems," presented at Optimization Days, 1977 IEEE Control Systems Society and SIAM, Montreal, Quebec, May 5-6, 1977.

[P18] B. T. Polyak, Zh. Vychisl. Mat. Mat. Fiz. 9, No. 3, pp. 509-521, 1969.

[P20] Proc. IEEE (Special Issue on CAD), pp. 1787-2005, November 1967.

[P21] Proc. IEEE (Special Issue on Computers in Design), pp. 6-118, January 1972.

R1 N. B. Rabbat and H. Y. Hsieh, IEEE Trans. Circuits and Systems, vol. CAS-23, no. 12, pp. 745-751, December 1976.

R2 M. N. Ransom and R. Saeks, Proc. 3rd Pittsburgh Symposium on Modelling and Simulation, University of Pittsburgh, 1973, vol. 4, pp. 224-228.

R3 _____, "Fault Isolation with Insufficient Measurements," IEEE Trans. on Circuit Theory, vol. CT-20, pp. 416-417, July 1973.

S1 S. Seshu and R. Waxman, IEEE Trans. on Reliability, vol. R-15, pp. 11-16, May 1965.

S2 R. Saeks, S. P. Singh and R. Liu, IEEE Trans. on Circuit Theory, vol. CT-19, no. 6, pp. 634-640, November 1972.

S3 A. Sangiovanni-Vincentelli, "A Graph Algorithm for the Optimal Tearing of a Sparse Matrix," Proc. 13th Annual Allerton Conf. on CAS, 1975.

S4 A. Sangiovanni-Vincentelli, "An Optimization Problem Arising from Tearing Methods," in J. Bunch and D. Rose (eds.),, Sparse Matrix Computations, pp. 97-110, Academic Press, 1976.

S5 A. Sangiovanni-Vincentelli, "The Complexity of an Optimization Problem Arising from Tearing Methods," Proc. 1976 European Conference on CAS, Genda, 1976.

S6 A. Sangiovanni-Vincentelli, L. K. Chen, and L. O. Chua, ERL Memorandum M-582, University of Callifornia, Berkeley, October 1976.

S7 A. Sangiovanni-Vincentelli and G. Guardabassi, IEEE Trans. on CAS, pp. 783-791, December 1976.

S8 A. Sangiovanni-Vincentelli, L. O. Chua, and L. K. Chen, "A New Tearing Approach: Node-Tearing Nodal Analysis," 1977 Proc. ISCAS, Phoenix, May 1977.

S9 A. Sangiovanni-Vincentelli, L. K. Chen, and L. O. Chua, "An Efficient Heuristic Cluster Algorithm for Tearing Large Scale Networks," to appear in IEEE Trans. on CAS.

S10 A. Sangiovanni-Vincentelli and T. A. Rickart, "Bipartite Graphs and an Optimal Bordered Triangular Form of a Matrix," submitted for publication.

S11 N. Sen and R. Saeks, Proc. 20th Midwest Symposium on Circuits and Systems, pp. 576-583, 1977.

S12 A. Sangiovanni-Vincentelli and V. Visvanathan, "DC Testing of Parametric Faults in Nonlinear Systems," IEEE International Symposium on Circuits and Systems, Houston, Texas, April 28-30, 1980.

S13 A. Sangiovanni-Vincentelli and E. Lelarasmee, "An Inner Approximations Algorithm for the Design of Electronic Circuits," International Symposium on Mathematical Theory of Networks and Systems, Delft, Holland, July 3-6, 1979.

S16 Z. Shor, Cybernetics, pp. 599-606, July 1974; Kibernetika, 4, pp. 65-70, 1972.

S22 SUPERSCEPTRE, Program made available by Dr. J. C. Bowers, University of South Florida, Tampa, Florida.

T1 T. N. Trick and R. T. Chien, IEEE Trans. on Circuits and Systems, vol. CAS-25, no. 1, pp. 46-48, January 1978.

T2 D. M. Topkis, Operations Res. 18, 3, pp. 404-413, 1970.

T3 D. M. Topkis, Operations Res. 18, 6, pp. 1216-1220, 1970.

T4 T. N. Trick and C. J. Aljajian, Proc. 20th Midwest Symposium on Circuits and Systems, pp. 576-583, 1977.

T5 T. N. Trick and A. A. Sakla, Proc. 1978 ISCAS, pp. 156-160, May 1978.

T6 T. N. Trick, W. Mayeda, and A. A. Sakla, Proc. 1979 ISCAS, pp. 878-881, July 1979.

W1 W. T. Weeks, et al., IEEE Trans. on Circuit Theory, vol. CT-20, pp. 628-634, November 1973.

W3 P. A. Wolfe, "A Method of Conjugate Subgradients for Minimizing Nondifferentiable Functions," in M. L. Balinski and P. Wolfe, (eds.), Nondifferentiable Optimization, Mat. Prog. Study 3, Amsterdam: North-Holland, pp. 145-173, 1975.

W5 F. F. Wu, IEEE Trans. Circuits and Systems, vol. CAS-23, no. 12, pp. 706-713, December 1976.

W6 L. Williamson and E. Polak, SIAM J. Control, vol. 14, no. 4, pp. 737-757, 1976; also ERL Memorandum M-424, University of California, Berkeley, November 29, 1973.

W7 Computer-Aided Design Techniques, E. Wolfendale (ed.), Butterworth's, London, 1970.

Z2 G. W. Zobrist and J. C. Bowers, "A Survey of Computer Aided Design and Analysis Programs," Proc. IEEE Conf. on CAD of Electronic and Microwave Circuits and Systems, pp. 140-146, July 1977.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: ISS-81-4 (terminating) — Last Year's No.(s): ISS-80-4

Title: VLSI Circuits for Future Computing Systems

Senior Principal Investigator(s):		
	A. M. Despain	(415) 642-5615
	D. A. Patterson	2-6587
	C. H. Sequin	2-5103

Scientific Objective

The objective of the research completed last year was to study architecture, design procedure and possible circuit implementations for very large scale integrated (VLSI) circuits to be used in computing systems of the future. Such chips will help to construct digital computers that are more reliable, less expensive, have higher performance and handle a level of complexity well beyond the capabilities of today's computers.

We used an interdisciplinary team to pool expertise from different fields such as innovative integrated circuit design, dynamic, non-Von-Newmann computer architecture, software directed hardware, computer aided design and optimization. With this team as a whole or with subgroups of it, we studied the basic issues in the relationship between VLSI chips and future computing systems. Out of this research, we got an understanding for the kind of chips that will be needed to build the computing systems of the next decade. A first phase has been concluded. More detailed research into specific related topics is now being pursued under separate grants from NSF and ARPA.

Abstract of Major Findings and Publications

The research during the two years of this grant focused on the organization of a large number of future single-chip computers into a well-organized network. In particular, optimal interconnection topologies and the relationship between topology and applications have been investigated. A second major issue concerned the switching hardware necessary to make message packet communication between these processors possible. The third study area concerned potential implementations of such single-chip computers in the time frame of the mid-1980's. [Sequin 79]

Interconnection topologies for single-chip computers

Various interconnection topologies based on binary tree structures have been studied. The binary tree is a particularly attractive interconnection topology in the context of large numbers of very large scale integration (VLSI) single-chip computers. The average path length between processors grows only logarithmically with the number of computers in the network, and the number of communication ports per node is kept reasonably low as required by the limited number of pins available on future VLSI chip packages. For improved total bandwidth, a more uniform message traffic distribution and the provision of redundant paths which is the basis for fault tolerance, the basic binary tree needs to be enhanced with additional links between nodes. Interconnecting nodes on the same level with horizontal links between nearest neighbors leads to half-ring and full-ring structures which have simple message routing algorithms and a reasonably good traffic distribution [Sequin et al 78].

Half-ring and full-ring trees, however, have certain shortcomings for computational problems which require a lot of communication between distant nodes in the tree, such as sorting of a very large data base distributed over all leaves of the tree. A study to find ways to alleviate these problems has led to a new structure, named "Hypertree," which combines some of

the best features of the binary tree with the compactness of an n-dimensional hyper-cube. The addition of suitably selected groups of n-cube links at each level of the binary tree provides short paths connecting those nodes the address of which differ in only one bit, i.e., pairs of nodes which need to exchange data rather frequently in algorithms such as sorting or Fast Fourier Transforms. A paper to report these findings has been submitted to IEEE Trans. on Computers.[Goodman, Sequin]

Dynamic simulation of message traffic

The various interconnection topologies mentioned above have been analyzed analytically with respect to average message path length for certain simple traffic patterns. For the more realistic and more complicated cases of messages originating with some statistical properties and communicating with different targets with different probabilities, e.g., because of a dependence on locality, the closed form analysis becomes too difficult. For these cases message traffic simulation for networks with up to 255 nodes have been performed on a VAX 11/780. Even though the simulation could run up to a million times slower than expected real time performance for the largest networks, significant insights could be gained with respect to potential bottlenecks in the network, suitable routing algorithms, the degree of time-multiplexing desirable on each link, and the buffering requirements in each node [Suhler and Despain 79], [Goldberg 79].

Relationship between topology and application

The performance of these networks of single-chip computers will depend to a significant degree on how well a particular problem can be mapped onto the basic tree structure. A first problem being investigated is the design of very large data base machines. Because massive amounts of data must be moved, the topology of the processor interconnections is important. To determine an appropriate interconnection scheme, a simple model of a very common but different data base operation is used to determine an optimal interconnection scheme. This is the elimination of duplicate information in a collection of data elements. In particular, four methods are considered which can perform the elimination of duplicates. Two involve the exhaustive comparison of all elements against each other, and two involve global sorting. These methods and their corresponding optimal interconnection topologies are analyzed and compared to help determine a suitable multiprocessor topology and computer architecture for a data base machine. A hybrid architecture is shown to be near-optimal under our assumptions [Goodman and Despain 80].

A second investigation has been started to determine how a database such as INGRES would fit onto the binary tree structure. Early results show, for example, if multi-relational queries are sent at the rate of one every five seconds, under a reasonable assumption for disks and communication rate, increasing the size of the tree from 15 to 63 processors increases the throughput twenty-fold. We have also found that for a tree of 255 processors, decreasing the number of disks from 64 to 16 disks only reduces the throughput twenty percent. Static placement of processes on processors gives better performance than random placement of processes on processors [Despain 80].

Processor architecture issues

A time frame for the potential implementation of the mentioned single-chip computers is the mid 1980's. By that time it will be possible to place about one million transistors on a single chip of silicon. While this number may seem large by present-day standards, it is certainly not infinite, and a judicious allocation of these transistors has to be made to the various different functions required in a processor in order to obtain best overall results. An investigation has been carried out to perform a tentative allocation of about a million transistors in such a manner that a powerful single-chip computer results.

One of the primary goals in this study was to realize as much primary memory of short access time on the chip as possible. The solution was to use an on-chip memory hierarchy composed of a substantial amount of high density dynamic random access memory, buffered through high-speed caches built from faster (and also large and more power consuming) static memory cells. Separate caches are being used for data, programs, microcode, addresses and descriptors. This results in a multiport memory which permits effective sharing of the limited amount of memory by these various types of information, resulting in increased flexibility and efficiency. On the whole, it turned out that most of the chip area is used by memory functions, since even the finite state machines used for control and other "random logic" functions are best implemented in a regularly structured, compact manner by

Communication between single-chip computers

The hardware required to provide efficient message packet communication between different nodes in the described network has been explored. A top level description has been outlined in [Sequin et al 78]. A prototype of a communication switch has been constructed with standard MSI and LSI TTL parts to verify these ideas. From the study of this prototype, the crucial building blocks within the communication hardware were identified and a suitable allocation of the available number of transistors on future VLSI chips to the various functions within the communication switch was proposed. This has led to the definition of general purpose VLSI components useful to efficiently interconnect single-chip computers of the mid-1980's [Sequin 80].

The main emphasis in the design of the interconnection networks and of the switching hardware has been to provide as much bandwidth as possible for communication between processors. Recently, it has become apparent that short latency time in establishing a message path to another node is of equal importance. In the first design, a substantial overhead was paid for the routing of the header of a new message and the setting up of a new virtual communication channel. To reduce latency time, the most important and time-consuming operations are now performed with special purpose hardware. A preliminary analysis indicates that routing of a message header through a node should ultimately be possible in less than ten clock cycles.

Support for languages and systems

Architectural support of operating systems and languages is clearly an important issue in multiprocessors. One of the drawbacks of the field has been the lack of a useful definition of high-level computer architectures; i.e., is the Intel 8080 a high-level language computer architecture because you can run a high-level language program on it? A review of the salient features of high-level computer language has clarified the fact that hardware and software have to be viewed together. This has led to some new insights of what constitutes a truly high-level computing system [Ditzel and Patterson 80].

Conclusions

During the two years of this research, insight has been gained into some of the relationships of the emerging VLSI technology and of mitable architectures for large distributed computing systems. While studies of various network topologies have found a conclusion, other issues are further pursued with separate funding. In practicular, research continues in the area of switching hardware, implementation studies of a VLSI processor with on-chip cache memory, and database application studies on tree structured networks.

The two year study concluded with this report has been very valuable to identify and formulate more specialized research issues in the vast field of VLSI computer architecture.

Publications

A. Under JSEP

Despain, A. M., "X-Tree: A Multiple Microcomputer System," COMPCON, San Francisco, Feb. 28, 1980, Digest, pp. 324-327.

Goldberg, W. S., "Communication in X-tree: A Simulator Supported Analysis," M.S. Thesis, University of California, Berkeley, July 1979.

Goodman, J. R. and A. M. Despain, "A Study of the Interconnection of Multiple Processors in a Data Base Environment," Conference on Parallel Processing, August 1980.

Goodman, J. R. and C. M. Sequin, "Hypertree, a Multiprocessor Interconnection Topology," submitted to IEEE Trans. Computers (Nov. 1979).

Patterson, D. A., E. Cott Fehr and C. H. Sequin, "Design Considerations for the VLSI Processor of X-tree," Proceedings 6th Annual Symposium on Computer Architecture, Philadelphia, Pa., April 23-25, 1979, pp. 90-101.

Sequin, C. H., "Instruction in MOS LSI Systems Design," Computer Magazine 13, No. 3, March 1980, pp. 67-73.

Sequin, C. H., and A. M. Despain and D. A. Patterson, "Communication in X-tree, a Modular Multiprocessor System," Proc. ACM 78, Washington, D.C., Dec. 4-6, 1978, pp. 194-203.

Sequin, C. H., "Single-Chip Computers, the new VLSI Building Blocks," Proc. VLSI Conference, Cal-Tech, Pasadena, CA, January 22-24, 1979.

Suhler, P. A. and A. M. Despain, "A Dynamic Traffic Simulator for the Analysis of a Multiprocessor System," Summer Simulation Conference, Toronto, Canada, July 17, 1979.

B. Under Other Sponsorship

Patterson, D. A., and C. H. Sequin, "Design Considerations for Single-Chip Computers of the Future," Joint Spec. Issue IEEE Jour. Solid State Circuits, SC-15, No. 1 and IEEE Trans. Computers, C-29, No. 2, Feb. 1980, pp. 108-116.

Sequin, C. H., "Message Switching Circuits for Multi-Microprocessors," COMPCON, San Francisco, Feb. 28, 1980, Digest pp. 328-334.

Ditzel, D. R. and D. A. Patterson, "Retrospective on High-Level Language Computer Architecture," Proc. of the 7th Intl. Symp. on Computer Architecture, May 1980, pp. 97-104.

References

[1]H. J. Manley, "Analysis-Synthesis of Connected Speech in Terms of Orthogonalized Exponentially Damped Sinusoids," J. Acoust. Soc. Amer., vol. 35, no. 4, April 1963, pp. 464-474.

[2]J. L. Flanagan, Speech Analysis, Synthesis, and Perception, 2nd ed., Springer-Verlag, N.Y., 1972.

[3]M. R. Schroeder, "Vocoders: Analysis and Synthesis of Speech," Proc. IEEE, vol. 54, May 1966, pp. 720-734.

[4]B. Gold and C. M. Rader, "The Channel Vocoder," IEEE Trans. Audio Electroacoustics, vol. AU-15, no. 4, Dec. 1967, pp. 148-160.

[5]R. W. Schafer and L. R. Rabiner, "Design and Simulation of a Speech Analysis-Synthesis System Based on Short-Time Fourier Analysis," IEEE Trans. Audio Electroacoustics, vol. Au-21, June 1973, pp. 165-174.

[6]B. Gold and L. R. Rabiner, "Analysis of Digital and Analog Formant Synthesizers," IEEE Trans. Audio Electroacoustics, vol. Au-16, Mar. 1968, pp. 81-94.

[7]B. S. Atal and S. L. Hanauer, "Speech Analysis and Synthesis by Linear Prediction of the Speech Wave," J. Acoust. Soc. Amer., vol. 50, 1971, pp. 637-655.

[8]J. Makhoul, "Linear Prediction: A Tutorial Review," Proc. IEEE, vol. 63, April 1975, pp. 561-580.

[9]A. V. Oppenheim and R. W. Schafer, "Homomorphic Analysis of Speech," IEEE Trans. Audio Electroacoustics, vol. Au-16, 1968, pp. 221-226.

[10]B. Gold, "Digital Speech Networks," Proc. IEEE, vol. 65, no. 12, Dec. 1977, pp. 1636-1658.

[11]A. V. Oppenheim, ed., Applications of Digital Signal Processing, Prentice-Hall Inc., N.J., 1978,

[12]L. R. Rabiner and B. Gold, Theory and Application of Digital Signal Processing, Prentice-Hall Inc., N.J., 1975.

[13]B. Widrow et al., "Adaptive Noise Cancelling: Principles and Applications," Proc. IEEE, vol. 63, Dec. 1975, p. 1692.

References, concluded

[14]B. Beek, E. P. Neuberg and D. C. Hodge, "An Assessment of the Technology of Automatic Speech Recognition for Military Applications," IEEE Trans. on Acous. Speech and Signal Proc., ASSP-25, no. 4, August 1977.

[15]R. Reddy, ed., Speech Recognition: Invited Papers of IEEE Symposium, Academic Press, New York, 1975.

[16]Man-Machine Communication by Voice, a special issue of Proceedings of the IEEE, April 1976.

[17]B. J. Hostica, R. W. Brodersen and P. R. Gray, "MOS Sampled-data Recursive Filters Using Switched Capacitor Integrators," IEEE Jour. of Solid-State Circuits, vol. SC-12, Dec. 1977, pp

[18]J. F. Albarran and D. A. Hodges, "A Charge-transfer Multiplying Digital-to-Analog Converter," IEEE Jour. of Solid-State Circuits, vol. SC-11, Dec. 1976, pp. 772-779.

[19]D. J. Allstot, R. W. Brodersen and P. R. Gray, "Fully-integrated High Order NMOS Sampled Data Ladder Filters," Int'l. Solid State Circuits Conf. Digest of Tech. Papers, 1978.

[20]P. I. Suciu and D. A. Hodges, "Image Contour Extraction with Analog MOS Circuit Techniques," IEEE Jour. of Solid-State Circuits, vol. SC-12, Feb. 1977, pp. 65-72.

[21]D. A. Hodges, P. R. Gray and R. W. Brodersen, "Potential of MOS Technology for Analog Integrated Circuits," IEEE Jour. of Solid-State Circuits, vol. SC-12, June 1977.

[22]C. R. Hewes, D. D. Buss and R. W. Brodersen, "Applications of CCD's to Speech Processing," Proc. of EASCON, Sept. 1977, Arlington, Va.

[23]J. Makhoul, "Stable and Efficient Lattice Methods for Linear Prediction," IEEE Trans. on Acous., Speech and Signal Proc., vol. ASSP-25, Oct. 1977, p. 423.

[24]R. W. Lucky, J. Salz and E. J. Weldon, Principles of Data Communication, McGraw-Hill, New York, 1968.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: ISS-81-6 (terminated) — Last Year's No.(s): None

Title: An Analytic Characterization of Image Objects

Senior Principal Investigators(s): D. J. Sakrison (415) 642-0253

Scientific Objective

Image Processing, in particular Feature Extraction and Image Coding, have been studied extensively for at least 15 - 20 years. Both problem areas are extremely important. Feature extraction is the crux of successful processing in diagnosis of medical images, analysis of reconnaissance photos, or monitoring parts assembly. Image encoding is similarly crucial in transmitting data back from a satellite or reconnaissance vehicle or in storing service manual diagrams, or a wealth of material in other applications. In spite of the importance of these areas, the problems have not really been solved. While clever ad hoc extraction and coding algorithms have been developed, it is safe to make two assertions:

1) The best of the extraction algorithms are not good enough to segment ordinary grey-scale images which contain arbitrary (non-test) objects.

2) In both the case of extraction or coding, not only is an "optimum" method not known, but the performance of the optimum extractor or coder is not known for comparison with computationally feasible methods.

The reason for this incomplete state of these two problem areas is the lack of any sort of model for the shape of image objects. Such an effective model would allow one to derive optimum algorithms and evaluate the effectiveness of practical algorithms relative to the optimum obtainable. Our objective is to develop such a model or model with the following attributes:

1) by appropriate selection of a modest number of parameters, one should be able to generate sample objects representative of the shapes of real objects in a variety of contexts: contour lines, structures in a reconnaissance scene, or symbols in a parts manual.

2) the model should allow one to determine an optimum processing (encoding or extraction) algorithm (or at least its structure) and obtain bounds on performance. Further, the model should allow one to determine to what extent advantage can be taken of global structure; i.e., how much better does an algorithm do that works with the whole raster than an algorithm that processes only one or several lines at a time? This will address the important issue of the relation between effectiveness of the processing and its computational complexity.

State of the Art

What is the current state of trying to model images and the objects contained therein? The problem of representing two-dimensional objects is basically different than representing a function of an independent variable,

and the standard methods of one-dimensional analysis and representation do not carry over. Grenander[1] has produced a scholarly treatise which provides an elegant structure for representing images, based on generators or primative elements. However, this structure does not really solve the problem, since it provides no insight or knowledge concerning what constitutes a reasonable or useful set of generators for image objects. Without this, the structure is useless. This choice of generators must be arrived at by a sense of empirical observations and mathematical gestalt that the community is currently lacking.

A number of mathematical models have been proposed on a line-by-line basis, usually assuming a Markov structure on a TV raster scan. However, these really beg the issue of representing the two-dimensional structure, and some produce sample images which reflect this one-dimensional ordering in a way that is quite disconsonant with the appearance of real images.

The only really satisfactory two-dimensional model to have been precisely formulated and extensively studied is the Ising model[2,3]. This study was initiated by physicists and has recently received some attention by mathematicians. This model generates objects of maximum entropy for a given average linear combination of perimieter and area. This model is interesting and could in fact realistically represent natural objects such as lakes or contour lines. However, it has some drawbacks. First, it does not represent more structured objects such as faces or man-made objects that appear in scenes. Secondly, it does not lend itself to calculations; e.g., calculation of the entropy rate of the Ising model is possible only numerically and only in certain sub-cases. Third, it is not a canonical representation of object shape: to obtain a natural or satisfactory appearing representation of a smooth object requires a very high sampling density (relative to the curvature of the object). Fourth, generation of sample objects with this distribution requires an iterative algorithm that uses extensive computer time.

A model representing objects as ruled surfaces has resulted in a useful code, but this model did not really represent or exploit the two-dimensional structure of the objects within the image[4]. Pavlides[5] considered a similar model constructed of planes and deduced some interesting properties of computing this representation from a sample image, but did not address the central problem of how to model the shapes (boundaries) of the planes.

Again we note that many useful encoding and extraction algorithms now exist, such as the Hueckel edge detection algorithm[6,7]. While such algorithms are clever and reasonably effective, they do not satisfactorily separate objects in real images, nor do they answer the question of whether such separation is possible and the computational cost required to achieve it.

Progress to Date

Our past and proposed work focuses around three approaches which we describe in sequence.

Two Component Coding of Grey-Scale Images

We have developed a coding algorithm[4] based on an image model which represents log|LOG-intensity across a scan line as a discontinuous component composed of straight-line segments plus a continuous Gaussian component representing texture. This method is quite effective, yielding better results than other codes we have seen and notably better results than a Transform Code. The method is limited in that the discontinuous component is modeled and processed line-by-line. This leave objectionable streaks and edge business and requires extra bits to encode the location of the break points of the line segments.

The algorithm for extracting the discontinuous or object component from a grey scale image has been modified to identify and align breakpoints on successive scan lines, identify planar regions and approximate them as such, and use a nonlinear estimator to smooth the breakpoint location. These improved descriptions have been used to improve the two-component image code.

Tree Generated Image Objects

We have developed and studied a model which generates objects by generating a tree or skeleton and then filling in smooth lines about the "bones" of the skeleton. To date we have generated sample objects from this model; these are similar in shape to objects such as tools or airplanes. We have also related errors along the edge to errors in the generating points and calculated the entropy necessary to transmit the objects' shape to within a specified accuracy. We are now in the process of calculating the rate required to describe these objects by the chain-link code discussed by Freeman[8] and Morin[9]. This work was primarily supported by JSEP.

The chain-link code has been investigated and better bounds were determined. By scanning sample objects, algorithms were determined which could be used for improved encoding techniques.

Curvature Description of Object Shape

We have completed an algorithm that can scan black-and-white images and determine a sequence of curvature pulses representing an object boundary. These pulses are used to drive a dynamic model which generates a smooth, pleasing approximation to the object boundary. The model incorporates feedback so that errors in position and angle do not accumulate.

This curvature based model has been used in two ways. First, curvature sequences for a variety of objects have been generated for the purpose of extracting a useful statistical model for these sequences. Second, the problem of coding these sequences taking advantage of the statistical properties has been examined.

References

[1] U. Grenander, Pattern Synthesis: Lectures in Pattern Theory, Volume 1, Springer Verlag, New York, 1976.

[2] R. Kindermann, J. Snell, Markov Random Fields, Dartmouth College, Department of Mathematics.

[3] H. Keston, "On the Number of Self-Avoiding Walks," Journal of Mathematical Physics I: vol. 4, No. 7, July 1963, II: vol. 5, No. 8, August 1964.

[4] J. Yan and D. Sakrison, "Encoding of Images Based on a Two-Component Source Model," IEEE Trans. on Comm., COM-25, Nov. 1977, pp. 1315-1322.

[5] T. Pavlides, "Segmentation of Pictures and Maps through Functional Approximation," Computer Graphics and Image Processing, 1972, pp. 360-372.

[6] M. H. Hueckel, "An Operator which Locates Edges in Digitized Pictures," Journal of the ACM, vol. 18, Jan. 1971, pp. 113-125.

[7] N. E. Nahi and M. H. Jahanshahi, "Image Boundary Estimation," IEEE Trans. on Computers, vol. C-26, Aug. 1977, pp. 772-781.

[8] H. Freeman, "Computer Processing of Line-Drawing Images," Computing Surveys, vol. 6, March 1974, pp. 57-96.

[9] T. Morin, "Chain-link Compression of Arbitrary Black-White Images," Computer Graphics and Image Processing, vol. 5, 1976, pp. 172-189.

B. CONSOLIDATED LIST OF PBULISHED JSEP PAPERS

THROUGH 31 AUGUST 1980

R. W. Coen R. S. Muller	1980	"Velocity of surface carriers in inversion layers on silicon," Solid State Electronics, v. 23, pp. 35-40.
P. Varaiya J. Walrand	1980	"A minimum principle for decentralized stochastic control problems,"Dynamic Optimization and Mathematical Economics, ed. Pan-Tai Liu, pp. 253-266.
C. D. Hartgring W. G. Oldham T-Y. Chiu	1980	"A mesfet model for circuit analysis," Solid-State Electronics, v. 23, pp. 121-126.
C. H. Sequin	1980	"Special feature: instruction in MOS LSI systems design," IEEE, pp. 67-73.
C. A. Desoer R-W. Liu J. Murray R. Saeks	6/80	"Feedback system design: the fractional representation approach to analysis and synthesis," IEEE Trans. on Automatic Control, v. AC-25, n. 3.
A. N. Payne E. Polak	6/80	"An interactive rectangle elimination method for biobjective decision making," IEEE Trans. on Automatic Control, v. AC-25, n. 3.
D. B. Rutledge S. E. Schwarz T.-L. Hwang D. J. Angelakos K. K. Mei S. Yokota	5/80	"Antennas and Waveguides for far-infrared integrated circuits," IEEE J. of Quantum Electronics, v. QE-16, n. 5.
L. O. Chua D. J. Curtin	5/80	"Synthesis of reciprocal piecewise-linear n-port resistors," IEEE Trans. on Circuits and Systems, v. CAS-27, n. 5.
C-Y. Chen S. Wang	4/80	"Narrow double-current-confinement channeled-substrate planar laser fabricated by double etching technique," Appl. Phys. Letters, v. 36, n. 8.
Y-C. Lin I. Adesida A. R. Neureuther	4/80	"Monte Carlo simulation of registration signals for electron beam microfabrication," Appl. Phys. Letters, v. 36, n. 8.
C. A. Desoer Y-T. Wang	4/80	"On the generalized nyquist stability criterion," IEEE Trans. on Automatic Control, v. AC-25, n. 2, pp. 187-196.
C-Y. Chen S. Wang	3/80	"Double-etching technique fo rthe fabrication of submicron channels on a GaAs wafer and its application to laser fabrication," J. Appl. Phys., v. 51, n. 3, pp. 1802-1808.

C. A. Desoer Y-T. Wang	2/80	"Foundations of feedback theory for nonlinear dynamical systems," IEEE Trans. on Cir. and Systems, v. CAS-27, n. 2, pp. 104-123.
M. Mansour E. I. Jury L. F. Chaparro	1979	"Estimation of the margin of stability for linear continuous and discrite systems," Int. J. Control, v. 30, n. 1, pp. 49-69.
C. A. Desoer Y. T. Wang	1979	"The robust non-linear servomechanism problem," Int. Journal on Control, v. 29, n. 5, pp. 803-828.
V. Borkar P. Varaiya	12/79	"Adaptive control of Markov chains, I: finite parameter set," IEEE Trans. on Auto. Control, v. AC-24, n. 6, pp. 953-957.
Y. C. Lin T. E. Everhart	12/79	"Study on volzage contrast in SEM," J. Vac. Sci. Technol., v. 16, n. 6, pp. 1856-1860.
K. Youssefi E. Wong	10/79	"Query processing in a relational database management system," Very Large Data Bases, Fifth International Conference on Very Large Data Bases, Rio de Janeiro, Brazil, pp. 409-417.
E. I. Jury L. F. Chaparro	10/79	"Remark on an equivalent relation in least square approximation," Proceedings of the IEEE, v. 67, n. 10, pp. 1444-1445.
E. Polak A. Sangiovanni-Vincentelli	9/79	"Theoretical and computational aspects of the optimal design centering, tolerancing, and tuning problem," IEEE Trans. on Cir. and Systems, v. CAS-26, n. 9, pp. 795-813.
S-H. Kwan C. T. Chuang R. S. Muller R. M. White	7/79	"Dual-Gate depletion-mode DMOS transistor for linear gain-control application," IEEE Trans. on Electron Devices, v. ED-26, n. 7, pp. 1053-1058.
C. Gonzaga E. Polak	7/79	"On constraint dropping schemes and optimality functions for a class of outer approximations algorithms," SIAM J. Control and Optimization, v. 17, n. 4, pp. 477-493.
E. Polak D. Q. Mayne	6/79	"On the finite solution of nonlinear inequalities," IEEE Trans. on Automatic Control, v. AC-24, n. 3, pp. 443-445.

P. A. S. Veloso	6/79	"Some remarks on multiple-entry finite automata," J. of Comp. and System Sciences, v. 18, n. 3, pp. 304-306.
J.M.P. Guedes C.W. Slayman T.K. Gustafson R.K. Jain	6/79	"Internal photoemission in AG-AL$_2$O$_3$-AL junctions," IEEE Journal of Quantum Electronics, v. QE-15, n. 6, pp. 475-481.
T.-L. Hwang S.E. Schwarz D.B. Rutledge	6/79	"Microbolometers for infrared detection," Applied Physics Letters, v. 34, n. 11, pp. 773-776.
Y. Yasuoka M. Heiblum T.K. Gustafson	6/15/79	"Coupling to an 'edge metal-oxide-metal' junction via an evaporated long antenna," Applied Physics Letters, 34(12), pp. 823-825.
D.W. Tsang S.E. Schwarz	5/79	"Transport theory of high-frequency rectification in Schottky barriers," 50(5), pp. 3459-3471.
B.S. Ting E.S. Kuh A. Sangiovanni-Vincentelli	4/79	"Via assignment problem in multilayer printed circuit board," IEEE Transactions on Circuits and Systems, v. CAS-26, n. 4, pp. 261-272.
C. Hu C. Drowley	1978	"Determination of diffusion length and surface recombination velocity by light excitation," Solid State Electronics, v. 21, pp. 965-968.
G.J. Korsh R.S. Muller	1978	"Conduction properties of lightly doped, polycrystalline silicon," Solid-State Electronics, v. 21, pp. 1045-1051.
D.J. Allstot R.W. Brodersen P.R. Gray	12/78	"MOS switched capacitor ladder filters," IEEE Journal of Solid-State Circuits, v. SC-13, n. 6, pp. 806-814.
G.M. Jacobs D.J. Allstot R.W. Brodersen P.R. Gray	12/78	"Design techniques for MOS switched capacitor ladder filters," IEEE Transactions on Circuits and Systems, v. CAS-25, n. 12, pp. 1014-1021.
H. Mukai E. Polak	12/78	"A second-order method for the general nonlinear programming problem," Journal of Optimization Theory and Applications, v. 26, n. 4, pp. 515-532.

H. Mukai E. Polak	12/78	"A second-order method for unconstrained optimization," Journal of Optimization Theory and Applications, v. 26, n. 4, pp. 501-513.
S.A.J. Druet B. Attal T.K. Gustafson J.P. Taran	10/78	"Electronic resonance enhancement of coherent anti-stokes Raman scattering," Physical Review, v. 18, n. 4, pp. 1529-1557.
C.L. McMaster	10/78	"An analysis of algorithms for the Dutch National Flag problem," Communications of the ACM, v. 21, n. 10, pp. 842-846.
T.K. Yee T.K. Gustafson	10/78	"Diagrammatic analysis of the density operator for nonlinear optical calculations: pulsed and cw responses," Physical Review A, v. 18, n. 4, pp. 1597-1617.
B. Zee	10/78	"Broadening mechanism in semiconductor (GaAs) lasers: limitations to single mode power emission," IEEE Journal of Quantum Electronics," v. QE-14, n. 10, pp. 727-736.
C.A. Desoer	9/78	"Perturbation in the I/O map of a non-linear feedback system caused by large plant perturbation," Journal of the Franklin Institute, v. 306, n. 3.
D.J. Allstot S.K. Lui T.S-T Wei P.R. Gray R.G. Meyer	8/78	"A new high-voltage analog-compatible I^2L process," IEEE Journal of Solid-State Circuits, v. SC-13, n. 4, pp. 479-482.
W.S. Chan Y.T. Wang	8/78	"A basis for the controllable canonical form of linear time-invariant multiinput systems," IEEE Transactions on Automatic Control, v. AC-23, n. 4, pp. 742-745.
W.Y. Lum T. Van Duzer	8/78	"Resonances in semiconductor-barrier Josephson junctions," Journal of Applied Physics, v. 49, pp. 4560-4563.
D.J. Allstot S.K. Lui T.S.T. Wei P.R. Gray R.G. Meyer	8/78	"A new high-voltage analog-compatible I^2L Process," IEEE Journal of Solid-State Circuits, v. SC-13, n. 4, pp. 479-483.

H. Mukai E. Polak	8/78	"On the use of approximations in algorithms for optimization problems with equality and inequality constraints," Siam J. on Numerical Analysis, v. 15, n. 4, pp. 674-693.
C. Hu	7/78	"Determination of nonuniform diffusion length and electric field in semiconductors," IEEE Transactions on Electron Devices, v. ED-25, n. 7, pp. 822-825.
W.Y. Lum H.W.K. Chan T. Van Duzer	7/78	"Switching measurements on Josephson memory loops," J. Appl. Phys., v. 49, n. 7, p. 4302.
C. Hu	5/78	"LED charge-control model and speed at high currents," Proc. of the IEEE, v. 66, n. 5, pp. 599-601.
B. S. Ting E. S. Kuh	5/78	"An approach to the routing of multilayer printed circuit boards," 1978 IEEE Intl. Symp. on Circuits and Systems Proceedings, Roosevelt Hotel, New York, New York, pp. 902-911.
F.M. Callier W.S. Chan C.A. Desoer	4/78	"Input-output stability of interconnected systems using decompositions: an improved formulation," IEEE Transaction on Automatic Control, v. AC-23, n. 2, pp. 150-163.
S. Goto E.S. Kuh	4/78	"An approach to the two-dimensional placement problem in circuit layout," IEEE Transactions on Circuits and Systems, v. CAS-25, n. 4, pp. 208-214.
N.R. Sandell, Jr. P. Varaiya M. Athans M.G. Safonov	4/78	"Survey of decentralized control methods for large scale systems," IEEE Transactions on Automatic Control, v. AC-23, n. 2, pp. 108-128.
M. Heiblum J.R. Whinnery T.K. Gustafson	3/78	"Characteristics of integrated MOM junctions at dc and at optical frequencies," IEEE Journal of Quantum Electronics, v. QE-14, n. 3, pp. 159-169.

A.L. Sangiovanni-Vincentelli Y.T. Wang	3/78	"On equivalent dynamic networks: elimination of capacitor loops and inductor cutsets," IEEE Transactions on Circuits and Systems, v. CAS-25, n. 3, pp. 174-177.
C.A. Desoer Y.T. Wang	2/78	"On the minimum order of a robust servocompensator," IEEE Transactions on Automatic Control, v. AC-23, n. 1, pp. 70-73.
M.P. Guedes T.K. Gustafson M. Heiblum D.P. Siu C.W. Slayman J.R. Whinnery Y. Yasuoka	2/78	"Photoinduced currents in metal-barrier-metal junctions," Radiation Energy Conversion in Space, Kenneth W. Billman, ed., American Institute of Astronautics and Aeronautics, New York, February 1978, pp. 524-548.
S.-H. Kwan R.M. White R.S. Muller	1977	"Integrated ultrasonic transducer," Ultrasonics Symp. Proc., IEEE Cat. #77CH1264-1SU, pp. 843-847.
B.J. Hosticka R.W. Brodersen P.R. Gray	12/77	"MOS sampled data recursive filters using switched capacitor integrators," IEEE Journal of Solid-State Circuits, v. SC-12, n. 6, pp. 600-608.
A. Sangionvanni-Vincentelli L.-K. Chen L.O. Chua	12/77	"An efficient heuristic cluster algorithm for tearing large-scale networks," IEEE Transactions on Circuits and Systems, v. CAS-24, n. 12, pp. 709-717.
J.K. Yan D.J. Sakrison	11/77	"Encoding of images based on a two-component source model," IEEE Transactions on Communications, v. COM-25, n. 11, pp. 1315-1322.
L. Figueroa D. Botez S. Wang	8/77	"Analysis of mode broadening due to transient heating of optically pumped semiconductor lasers," IEEE Journal of Quantum Electronics, v. QE-13, n. 8, pp. 612-625.

C. A. Desoer F. M. Callier W. S. Chan	7/77	"Robust of stability conditions for linear time-invariant feedback systems," IEEE Transactions on Automatic Control, v. AC-22, n. 4, pp. 586-590.
E. I. Jury V. R. Kolavennu B. D. O. Anderson	6/77	"Stabilization of certain two-dimensional recursive digital filters," Proceedings of the IEEE, v. 65, n. 6, pp. 887-892.
M. S. Chung T. E. Everhart	5/77	"Role of plasmon decay in secondary electron emission in the nearly-free-electron metals," Physical Review B, v. 15, n. 10, pp. 4699-4715.
L. Figueroa D. Botez S. Wang	5/77	"Broadening of the longitudinal mode due to transient heating in optically pumped semiconductor lasers," Journal of Applied Physics, v. 48, n. 5, pp. 1995-1997.
D. Goodman	4/77	"Some stability properties of two-dimensional linear shift-invariant digital filters," IEEE Transactions on Circuits and Systems, v. CAS-24, n. 4, pp. 201-208.
W. Y. Lum T. Van Duzer	4/77	"Switching measurements on semiconductor-barrier Josephson junctions," Journal of Applied Physics, v. 48, n. 4, pp. 1693-1696.
J. F. Hunka R. E. Stovall D. J. Angelakos	3/77	"A technique for the rapid measurement of bistatic radar cross sections," IEEE Transactions on Antennas and Propagation, v. AP-25, n. 2, pp. 243-248.
P. I. Suciu D. A. Hodges	2/77	"Image contour extraction with analog MOS circuit techniques," IEEE Journal on Solid-State Circuits, v. SC-12, n. 1, pp. 65-72.

B. D. O. Anderson E. I. Jury	1/77	"A 'Simplest possible' property of the generalized Routh-Hurwitz conditions," SIAM Journal on Control and Optimization, v. 15, n. 1, pp. 177-184.
R. Boel P. Varaiya	1/77	"Optimal control of jump processes," SIAM Journal on Control and Optimization, v. 15, n. 1, pp. 92-119.
J. F. Albarran D. A. Hodges	12/76	"A charge-transfer multiplying digital-to-analog converter," IEEE Journal of Solid-State Circuits, v. SC-11, n. 6, pp. 772-779.
F. M. Callier W. S. Chan C. A. Desoer	12/76	"Input-output stability theory of interconnected systems using decomposition techniques," IEEE Transactions on Circuits and Systems, v. CAS-23, n. 12, pp. 714-729.
B. S. Ting E. S. Kuh I. Shirakawa	12/76	"The multilayer routing problem: algorithms and necessary and sufficient conditions for the single-row single-layer case," IEEE Transactions on Circuits and Systems, v. CAS-23, n. 12, pp. 768-778.
D. Botez L. Figueroa S. Wang	10/76	"Optically pumped GaAs-$Ga_{1-x}Al_xAs$ half-ring laser fabricated by liquid-phase epitaxy over chemically etched channels," Applied Physics Letters, v. 20, n. 8, pp. 502-504.
D. Goodman	10/76	"An alternate proof of Huang's stability theorem," IEEE Transactions on Acoustics, Speech, and Signal Processing, pp. 426-427.
R. K. Jain T. K. Gustafson	9/76	"Efficient generation of continuously tunable coherent radiation in the 2460-2560-A spectral range," IEEE Journal of Quantum Electronics, pp. 555-556.

M. Stonebraker E. Wong P. Kreps G. Held	9/76	"The design and implementation of INGRES," ACM Transactions on Database Systems, v. 1, n. 3, pp. 189-222.
C-C. Tseng D. Botez S. Wang	7/76	"Optically pumped epitaxial GaAs waveguide lasers with distributed Bragg reflectors," IEEE Journal of Quantum Electronics Correspondence, pp. 549-551.
E. Wong K. Youssefi	9/76	"Decomposition - a strategy for query processing," ACM Transactions on Database Systems, v. 1, n. 3, pp. 223-241.
B. D. O. Anderson E. I. Jury	8/76	"Generalized Bezoutian and Sylvester matrices in multivariable linear control," IEEE Transactions on Automatic Control, pp. 551-556.
R. A. Heald D. A. Hodges	8/76	"Multilevel random-access memory using one transistor per cell," IEEE Journal of Solid-State Circuits, v. SC-11, n. 4, pp. 519-528.
O. Teschke A. Dienes J. R. Whinnery	7/76	"Theory and operation of high-power CW and long-pulse dye lasers," IEEE Journal of Quantum Electronics, v. QE-12, n. 7, pp. 383-395.
C. L. Huang	6/76	"Schottky diodes and other devices on thin silicon membranes," IEEE Transactions on Electron Devices, v. ED-23, n. 6, pp. 579-583.
Y-K. Lee S. Wang	6/76	"Electrooptic Bragg-deflection modulators: theoretical and experimental studies," Applied Optics, v. 15, n. 6, pp. 1565-1572.
Y-K. Lee S. Wang	5/76	"Electrooptic guided-to-unguided mode converter," IEEE Journal of Quantum Electronics, v. QE-12, n. 5, pp. 273-281.

P. Varaiya	5/76	"N-player stochastic differential games," SIAM Journal on control and optimization, v. 14, n. 3, pp. 538-545.
D. Botez W. T. Tsang S. Wang	2/76	"Growth characteristics of GaAs-$Ga_{1-x}Al_xAs$ structures fabricated by liquid-phase epitaxy over preferentially etched channels," Applied Physics Letters, v. 28, n. 4, pp. 234-237.
L. O. Chua S. M. Kang	2/76	"Memristive devices and systems," Proceedings of the IEEE, v. 64, n. 2, pp. 209-223.
D. A. Hodges	2/76	"Trends in computer hardware technology," Computer Design, pp. 77-85.
T-L. Hwang S. E. Schwarz R. K. Jain	2/76	"Plasma radiation from tunnel junctions," Physical Review Letters, v. 36, n. 7, pp. 379-382.
C. H. Lin J. P. Heritage T. K. Gustafson R. Y. Chiao J. P. McTague	2/76	"Birefringence arising from the reorientation of the polarizability anisotropy of molecules in collisionless gases," Physical Review A, v. 13, n. 2, pp. 813-829.
M. J. Chien E. S. Kuh	1976	"Solving piecewise-linear equations for resistive networks," Circuit Theory and Applications. v. 4, pp. 3-24.
L. O. Chua A. Ushida	1976	"A switching-parameter algorithm for finding multiple solutions of nonlinear resistive circuits," Circuit Theory and Applications, v. 4, pp. 215-239.
P. I. Hagouel A. R. Neureuther	1976	"Modeling validation, techniques and applications for X-ray lithography," Electron and Ion Beam Science and Technology, Seventh International Conference, p. 190-197.
M. Magidin A. Gill	1976	"Singular shift registers over residue class rings," Mathematical Systems Theory, v. 9, n. 4, pp. 345-358.

E. Polak A. N. Payne	1976	"On multicriteria optimization," Directions in Large Scale Systems, pp. 77-94.
L. W. Braverman	12/75	"Controlled passive Q switch for the N_2-laser-pumped dye laser," Applied Physics Letters, v. 27, n. 11, pp. 602-604.
Z. A. Yasa O. Teschke L. W. Braverman A. Dienes	11/75 12/75	"Picosecond pulses from passively mode-locked dye lasers," Optics Communications, v. 15, n. 3, pp. 354-357.
G. W. Hughes R. M. White	10/75	"Microwave properties of non-linear MIS and Schottky-barrier microstrip," IEEE Transactions on Electron Devices, v. ED-22, n. 10, pp. 945-956.
Z. A. Yasa O. Teschke	10/75	"Picosecond pulse generation in synchronously pumped dye lasers," Optics Communications, v. 15, n. 2, pp. 169-172.
D. A. Hodges	8/75	"A review and projection of semiconductor components for digital storage," Proceedings of the IEEE, v. 63, n. 8 pp. 1136-1147.
A. I. Mees A. R. Bergen	8/75	"Describing functions revisited," IEEE Transactions on Automatic Control, v. AC-20, n. 4, pp. 473-478.
C-C. Tseng D. Botez S. Wang	6/75	"Optical bends and rings fabricated by preferential etching," Applied Physics Letters, v. 26, n. 12, pp. 699-701.
B-L. Twu S. E. Schwarz	6/75	"Properties of infrared cat-whisker antennas near 10.6μ, Applied Physics Letters, v. 26, n. 12, pp. 672-675.
P. S. Cross W. G. Oldham	5/75	"Theory of optical-gain measurements," IEEE Journal of Quantum Electronics, v. QE-11, n. 5, pp. 190-197.

D. J. Sakrison	5/75	"Worst sources and robust codes for difference distortion measures," IEEE Transactions on Information Theory, Vol. IT-21, No. 3, pp. 301-309.
R. E. Stovall K. K. Mei	5/75	"Application of a unimoment technique to a biconical antenna with inhomogeneous dielectric loading," IEEE Transactions on Antennas and Propagation, Vol. AP-23 No. 3, pp. 335-342.
C. A. Desoer	4/75	"Plant perturbations in nonlinear multivariable feedback system," Journal of the Franklin Institute, Vol. 29, No. 4, pp. 279-282.
O. Teschke A. Dienes G. Holtom	3/75	"Measurement of triplet lifetime in a jet stream CE dye laser," Optics Communications, Vol. 13, No. 3, pp. 318-320.
M. S. Chung	1/75	"Improved calculations of secondary electron energy distributions of metals," Journal of Applied Physics, Vol. 46, No. 1, pp. 465-466.
P. Antognetti W. G. Oldham	1975	"The role of ionization coefficient in the operation of avalanche diodes above breakdown," Journal of Electronic Materials, Vol. 4, No. 1, pp. 77-90.
H. Mukai E. Polak	1975	"A quadratically convergent primal-dual algorithm with global convergence properties for solving optimization problems with equality constraints," Mathematical Programming, v. 9, pp. 336-349.
W. G. Oldham P. Antognetti	1975	"An approximate turn-off theory for miniature avalanche diodes," phys. stat. sol. (a) 28, 555, pp. 555-559.

P. I. Suciu D. A. Hodges	1975	"Image contour extraction with analog MOS circuit techniques," SID 75 Digest, pp. 68-69.
S-H. Wang E. J. Davison	1975	"Design of decoupled control systems. A frequency comain approach," Int. Journal Control, Vol. 21, No. 4, pp. 529-536.
G. R. Boyle B. M. Cohn D. O. Pederson J. E. Solomon	12/74	"Macromodeling of integrated circuit operational amplifiers," IEEE Journal of Solid-State Circuits, Vol. SC-9, No. 6, pp. 353-364.
B. Y. Kamath R. G. Meyer P. R. Gray	12/74	"Relationship between frequency response and settling time of operational amplifiers," IEEE Journal of Solid-State Circuits, Vol. SC-9, No. 6, pp. 347-352.
B-L. Twu S. E. Schwarz	11/74	"Mechanism and properties of point-contact metal insulator-metal diode detectors at 10.6μ," Applied Physics Letters, Vol. 25, No. 10, pp. 595-598.
C. A. Desoer	10/74	"Multivariable systems: Factorization of det(I +FG) as a product of measurable gains," IEEE Transactions on Automatic Control, Vol. AC-19, No. 5, p. 606.
L. K. Cheung E. S. Kuh	9/74	"The bordered triangular matrix and minimum essential sets of a digraph," IEEE Transactions on Circuits and Systems, Vol. CAS-21, No. 5, pp. 633-639.
M. S. Chang	8/74	"Tolerance to the phase-matching condition for the integrated acoustic filter," Applied Optics, Vol. 13, pp. 1867-1871.
A. Gill L. T. Kou	8/74	"Multiple-entry finite automata," Journal of Computer and Systems Sciences, Vol. 9, No. 1, pp. 1-19.
Y-K. Lee S. Wang	8/74	"Tantalum oxide light guide on lithium tantalate," Applied Physics Letters, Vol. 25, No. 3, pp. 164-166.

E. Polak	6/74	"A globally converging secant method with applications to boundary value problems," SIAM J. Numerical Anal., Vol. 11, No. 3, pp. 529-537.
E. Polak	6/74	"A modified secant method for unconstrained minimization," Mathematical Programming, Vol. 6, No. 3, pp. 264-280.
J. L. Gates R. M. White	5/74	"Surface-acoustic-wave phase shifter using electrical depolarisation," Electronics Letters, Vol. 10, No. 11.
P. R. Gray R. G. Meyer	5/74	"Recent advances in monolithic operational amplifier design," IEEE Transactions on Circuits and Systems, Vol CAS-21, No. 3, pp. 317-327.
P. R. Gray D. J. Hamilton J. D. Lieux	4/74	"Analysis and design of temperature stabilized substrate integrated circuits," IEEE Journal of Solid-State Circuits, Vol. SC-9, No. 2, pp. 61-69.
C. Haug J. R. Whinnery	4/74	"Experiments on transverse mode locking of circular cylindrical optical beams and certain flat beams," IEEE Journal of Quantum Electronics, Vol. QE-10, No. 4, pp. 406-408.
A. R. Neuruether F. H. Dill	4/74	"Photoresist modelling and device fabrication applications," Proceedings of the Symposium on Optical and Acoustical Micro-Electronics, New York.
J. T. C. Chen R. S. Muller	2/74	"Carrier mobilities at weakly inverted silicon surfaces," Journal of Applied Physics, Vol. 45 No. 2, pp. 828-834.
M. S. Chung T. E. Everhart	2/74	"Simple calculation of energy distribution of low-energy secondary electrons emitted from metals under electron bombardment," Journal of Applied Physics, Vol. 45, No. 2, pp. 707-709.

C. Chen	1/74	"Realizability of communication nets: an application of the Zadeh criterion," IEEE Transactions on Circuits and Systems, Vol. CAS-21, No. 1, pp. 150-151.
C. A. Desoer J. D. Schulman	1/74	"Zeros and poles of matrix transfer functions and their dynamical interpretation," IEEE Transactions on Circuits and Systems, Vol. CAS-21 No. 1, pp. 3-8.
A. Gill D. Gottlieb	1/74	"The identification of a set by successive intersections," Information and Control, Vol. 24, No. 1, pp. 20-35.
M. A. Morgan S. Silver	1/74	"Transformation of the spectrum of a signal in communication between relativistically moving inertial frames," IEEE Transactions on Aerospace and Electronic Systems, Vol. AEC-10, No. 1, pp. 82-93.
R. K. Jain A. Dienes	1974	"Polychromatic N_2 laser-pumped dye lasers," Spectroscopy Letters, 7(10), pp. 491-501.
A. R. Neureuther P. I. Hagouel	1974	"X-Ray lithographic fabrication of blazed diffraction gratings," Proceedings of the Electron and ION Beam Science and Technology, pp. 23-33.
J. S. Seto T. Van Duzer	1974	"Theory and measurement of lead-tellurium-lead supercurrent junctions," Low Temperature Physics-LT-13, Vol. 3, pp. 328-333.
S. Takeda A. R. Bergen	12/73	"Instability of feedback systems by orthogonal docomposition of L_2," IEEE Transactions of Automatic Control, Vol. AC-18, No. 6, pp. 630-636.
O. Teschke A. Dienes	10/73	"Solvent effects of the triplet state population in jet stream CW dye lasers," Optics Communications, Vol. 9, No. 2, pp. 128-131.
A. Dienes M. Madden	9/73	"Study of excitation transfer in cye mixtures by measurements of gain spectra," Journal of Applied Physics, Vol. 44, No. 9, pp. 4161-4164.

D. A. Hodges	9/73	"Alternative component technologies for advanced memory systems," IEEE Computer Magazine, Vol. 6, No. 8, pp. 35-37.
C. A. Desoer J. D. Schulman	8/73	"Cancellations in multivariable continuous-time and discrete-time feedback systems treated by greatest common divisor extraction," IEEE Transactions on Automatic Control, Vol. AC-18, No. 4, pp. 401-402.
R. A. Heald D. A. Hodges	8/73	"Design of Schottky-barrier diode clamped transistor layouts," IEEE Journal of Solid-State Circuits, Vol. SC-8, No. 4, pp. 269-275.
R. K. Jain T. K. Gustafson	8/73	"Second-harmonic generation of several argon-ion laser lines," IEEE Journal of Quantum Electronics, Vol. QE-9, No. 8, pp. 859-861.
R. K. Jain C. Hu T. K. Gustafson S. S. Elliot M. S. Chang	7/73	"Absorption processes associated with anti-Stokes fluorescence in rhodamine B solutions," Journal of Applied Physics, Vol. 44, No. 7, pp. 3157-3161
C. Lin T. K. Gustafson A. Dienes	7/73	"Superradiant picosecond laser emission from transversely pumped dye solutions," Optics Communications, Vol. 8, No. 3, pp. 210-215.
S. Swierkowski T. Van Duzer C. W. Turner	7/73	"Amplification of acoustic surface waves in piezoelectric semiconductors," IEEE Transactions on Sonics and Ultrasonics, Vol. SU-20, No. 3, pp. 260-267.
A. Dienes R. K. Jain C. Lin	6/73	"Formation mechanisms in an excited-state-reaction dye laser," Applied Physics Letters, Vol. 22, No. 12, pp. 632-634.
R. G. Meyer L. Nagel S. K. Lui	6/73	"Computer simulation of 1/f noise performance of electronic circuits," IEEE Journal of Solid-State Circuits, Vol. SC-8, No. 3, pp. 237-240.

E. Polak	4/73	"An historical survey of computational methods in optimal control," SIAM Review, Vol. 15, No. 2, pp. 553-584.
E. R. Lewis C. W. Li	3/73	"Evidence concerning the morphogenesis of saccular receptors in the bullfrog (Rana catesbeiana)," Journal of Cell Biology, Vol. 139, No. 3, pp. 351-361. [JSEP supported only the instrumentation which was for general use].
A. H. Piekara T. K. Gustafson	3/73	"The interaction of vibrational enhancement and the orientational Kerr effects in liquids," Optics Communications, Vol. 7, No. 3, pp.197-200.
C. Hu J. R. Whinnery	1/73	"A new thermo-optical measurement method and a comparison with other methods," Applied Optics, Vol. 12, No. 1, pp. 12-19.
O. Pironneau E. Polak	1/73	"Rate of convergence of a class of methods of feasible directions," SIAM Journal of Numerical Analysis, Vol. 10, No. 1, pp. 161-174.
J. R. Fiebiger R. S. Muller	1973	"Surface lifetime degradation in Si and Ge under low energy electron irradiation," Surface Science, Vol. 63, pp. 544-557.
W. M. Gosney R. S. Muller	12/72	"Aluminum oxide films made from evaporated sapphire," Thin-Solid Films, Vol. 14, No. 2, pp. 255-266.
G. W. Hughes R. M. White	11/72	"MIS and Schottky barrier microstrip devices," Proceedings IEEE, Vol. 60 No. 11, pp. 1460-1461.
T. Fujisawa E. S. Kuh T. Ohtsuki	11/72	"A sparse matrix method for analysis of piecewise-linear resistive networks," IEEE Transactions of Circuit Theory, Vol. CT-19, No. 6, pp. 571-584.
T. K. Gustafson C. H. Townes	10/72	"Influence of steric effects and compressibility of nonlinear response to laser pulses and the diameters of self-trapped filaments," The Physical Review, Vol. 6, No. 4,

E. Polak	10/72	"A survey of methods of feasible directions for the solution of optimal and control problems," IEEE Transactions on Automatic Control, Vol. AC-17, No. 5, pp. 591-596.
C. A. Desoer H. Haneda	9/72	"The measure of a matrix as a tool to analyze computer algorithms for circuit analysis," IEEE Transactions on Circuit Theory, Vol. CT-19, No. 5, pp. 480-486.
T. E. Everhart M. S. Chung	9/72	"Idealized spatial emission distribution of secondary electrons," Journal of Applied Physics, Vol. 43, No. 9, pp. 3707-3711.
W. G. Oldham R. R. Samuelson P. Antognetti	9/72	"Triggering phenomena in avalanche diodes," IEEE Transactions on Electronic Devices, Vol. ED-19, No. 9 pp. 1056-1060.
M. M. Matluk A. Gill	9/72	"Decomposition of linear sequential circuits over residue class rings," Journal of the Franklin Institute, Vol. 294, No. 3, pp. 167-180.
A. Bahraman W. G. Oldham	8/72	"The temperature variation of the electron diffusion length and the internal quantum efficiency in GaAs electroluminescent diodes," Solid State Electronics, Vol. 15,pp. 907-917.
E. R. Lewis	8/72	"Delay-line models of opoulation growth," Ecology, Vol. 53, No. 5, pp. 797-807.
J. R. Fiebiger R. S. Muller	7/72	"Pair production energies in silicon and germanium bombarded with low-energy electrons," Journal of Applied Physics, Vol. 43, No. 7, pp. 3202-3207.
J. D. Hagopian I. T. Frisch	7/72	"Capacitance, inductance, and resistance minimization in RLC networks," IEEE Transactions on Circuit Theory, Vol. CT-19, No. 4, pp. 383-385.
A. Bahraman W. G. Oldham	5/72	"Role of copper in the degradation of GaAs electroluminescent diodes," Journal of Applied Physics, Vol. 43, No. 5, pp. 2383-2387.

A. V. Nurmikko S. E. Schwarz	5/72	"Preparation and detection of large coherent polarizations in resonant media," Applied Physics Letters, Vol. 20, No. 9, pp. 346-348. .
P. M. Spira	5/72	"Complete linear proofs of systems of linear inequalities," Journal of Computer and System Sciences, Vol. 3, No. 3, pp. 205-216.
S. H. Wang C. A. Desoer	5/72	"The exact model matching of linear multivariable systems," IEEE Transactions on Automatic Control, Vol. AC-17, No. 3, pp. 347-349.
S. Wang M. Shah J. D. Crow	4/72	"Studies of the use of gyrotropic and anisotropic materials for mode conversion in thin-film optical-waveguide applications," Journal of Applied Physics, Vol. 43, No. 4, pp. 1861-1875.
O. Pironneau E. Polak	4/72	"On the rate of convergence of of certain methods of centers," Mathematical Programming, Vol. 2, No. 2, pp. 230-257.
A. R. Bergen R. A. Baker	4/72	"On the third-order systems and Alzerman's conjecture," IEEE Transactions on Automatic Control, Vol. AC-17, No. 2, pp. 220-222.
M. S. Chang P. Burlamacchi C. Hu J. R. Whinnery	4/72	"Light amplification in a thin film," Applied Physics Letters, Vol. 20,No. 8, pp. 313-314.
P. S. Cross W. G. Oldham	2/72	"Monolithic measurement of optical and absorption in PbTe," Journal of Applied Physics, Vol. 46,No. 2, pp. 952-954.
R. A. Skoog C. Lau	2/72	"Instability of slowly varying systems," IEEE Transactions on Automatic Control, Vol. 72, No. 1, pp. 86-92.
S. Wang M. Shah J. D. Crow	2/72	"Wave propagation in thin-film optical waveguide using gyrotropic and anisotropic materials as substrates," IEEE Journal of Quantum Electronics, Vol. QE-8, No. 2, pp. 212-216.

J. D. Hagopian I. T. Frisch	1/72	"Capacitance and resistance minimization in n-port RC networks," IEEE Transactions on Circuit Theory, Vol. CT-19, No. 1, pp. 87-89.
R. A. Skoog	1/72	"Some results concerning time-varying networks having a time-invariant terminal behavior," IEEE Transactions on Circuit Theory, Vol. CT-19, No. 1, pp. 48-52.
S. H. Wang	1972	"Relationship between triangular decoupling and invertivility of linear multivariable systems," International Journal of Control, Vol. 15, No. 2, pp. 395-399.
W. G. Oldham P. Antognetti R. R. Samuelson	12/71	"A new method for breakdown voltage determination in p-n junction," Applied Physics Letters, Vol. 19, No. 11, pp. 466-467.
J. Seto T. Van Duzer	12/71	"Supercurrent tunneling junctions with tellurium barriers," Applied Physics Letters, Vol. 19, No. 11, pp. 488-491.
B. A. Wooley S-Y. J. Wong D. O. Pederson	12/71	"A computer aided evaluation of the 741 amplifier," IEEE Journal of Solid State Circuits, Vol. SC-6 No. 6, pp. 357-366.
T. E. Everhart P. H. Hoff	12/71	"Determination of kilovolt electron energy dissipation vs. penetration distance in solid materials," Journal of Applied Physics, Vol. 42, No. 13, pp. 5837-5846.
I. Getreu I. McGregor	12/71	"An integrated class B hearing-aid amplifier," IEEE Journal of Solid State Circuits, Vol. SC-6, No. 6, pp. 376-384.
R. N. Biswas E. S. Kuh	11/71	"A multi-parameter sensitivity measure for linear systems," IEEE Transactions on Circuit Theory, Vol. CT-18, No. 6, pp. 718-719.
R. N. Biswas E. S. Kuh	11/71	"Optimum synthesis of a class of multiple-loop feedback systems," IEEE Transactions of Circuit Theory, Vol. CT-18, No. 6, pp. 582-587.

K. Zaki A. R. Neureuther	11/71	"Scattering from a perfectly conducting surface with a sinusoidal height profile: TM polarization," IEEE Transactions on Antennas and Propagation, Vol. AP-19, No. 6, pp. 747-751.
W. Borgest P. Varaiya	10/71	"Target function approach to linear pursuit problems," IEEE Transactions on Automatic Control, Vol. AC-16, No. 5, pp. 449-459.
S. S. Naik W. G. Oldham	10/71	"Neutron radiation effects in junction field-effect transistors," IEEE Trans. on Nuclear Science, Vol. NS-18, No. 10, p. 9.
A.V. Nurmikko	9/71	"A CO_2 laser-triggered spark gap," IEEE Journal of Quantum Electronics, Vol, QE-7, No. 9.
S. Wang J. D. Crow M. Shah	9/71	"Studies of magnetooptic effects for thin-film optical-waveguide Applications," IEEE Trans on Magnetics, Mol. MAG-7, No. 3, pp. 385-387.
S. Wang J. D. Crow M. Shah	9/71	"Thin-film optical waveguide mode converters using gyrotropic and anisotropic substrates," Applied Physics Letter, Vol. 19, No. 6, pp. 187-189.
E. Wong T. C. Chiang	9/71	"Canonical structure in attribute based file orgainzation," Comm. of the ACM, Vol. 14, No. 9, pp. 593-597.
T. E. Idleman F. S. Jenkins W. J. McCalla	8/71	"SLIC-a simulator for linear intregrated circuits," IEEE Journal of Solid-State Circuits, Vol. SC-6, No. 4, pp. 188-213.
L. Nagel R. Rohrer R. Meyer L. Weber	8/71	"Computationally efficient electronic circuit noise calculations," IEEE Journal of Solid-State Circuits, Vol. SC-6, No. 4, pp. 205-213.
C. Hu R. S. Muller	7/71	"A resistive-gated IGFET tetrode," IEEE Trans. on Electron Devices, Vol. ED-18, No. 7, pp. 418-425.

P. M. Russo R. A. Rohrer	5/71	"The tree-link approach to the transient analysis of a class of nonlinear networks," IEEE Trans. on Circuit Theory, Vol. CT-18, No. 3, pp. 400-403.
P. W. Smith T. Hansch	3/71	"Cross-relaxation effects in the saturation of the 6328 Å neon-laser line," Physical Review Letters, Vol. 26, No. 13, pp. 740-743.
W. J. McCalla W. G. Howard, Jr.	2/71	"Bias-3--A program for the non-linear DC analysis of bipolar transistor circuits," IEEE Journal of Solid-State Circuits, Vol. SC-6, No. 1, pp. 14-19.
A. V. Nurmikko S. E. Schwarz	2/71	"Optical nutation echo in degenerate resonant systems," Optics Communicaitons, Vol. 2, No. 9, pp. 416-418.
A. V. Nurmikko T. A. DeTemple S. E. Schwarz	2/71	"Single-mode operation and mode locking of high pressure CO_2 lasers by means of saturable absorbers," Applied Physics Letters, Vol. 18, No. 4, pp. 130-132.
B. A. Wooley	2/71	"The automated design of DC-coupled, monolithic broadband amplifiers," IEEE Journal of Solid-State Circuits, Vol. SC-6, No. 1, pp. 24-34.
R. I. Dowell	1/71	"Automated design of biasing circuits," IEEE Trans. on Circuit Theory, Vol. CT-18, No. 1, pp. 85-89.
W. J. McCalla	1/71	"Elements of computer-aided circuit analysis," IEEE Trans. on Circuit Theory, Vol. CT-18, No. 1, pp. 14-26.
P. M. Russo R. A. Rohrer	1/71	"Computer optimization of the transient response of an ECL gate," IEEE Trans. on Circuit Theory, Vol. CT-18, No.1, pp. 197-199.

P. M. Russo	1/71	"On the time-domain analysis of linear time-invariant networks by digital computer," IEEE Trans. on Circuit Theory, CT-18, No. 1, pp. 194-197.
E. S. Kuh	1971	"Circuits, feedback, and dynamical systems," Systems and Control, Vol. 15, No. 3, pp. 204-212.
J. K. Aggarwal	12/70	"Computation of optimal control for time-delay systems," IEEE Trans. on Automatic Control, Vol. AC-15, No. 6, pp. 683-685.
K. K. Pang	11/70	"Cascade synthesis of distributed networks by lumped ladder RC Equivalents," IEEE Trans. on Circuit Theory, Vol. CT-17, No. 4, pp. 549-554.
S. H. Wang	10/70	"Design of precompensator for decoupling problem," Electronics Letters, Vol. 6, No. 23.
F. M. Tesche A. R. Neureuther	9/70	"Radiation patterns for two monopoles on a perfectly conducting sphere," IEEE Trans. on Antennas and Propagation, Vol. AP-18, No. 5, pp. 690-694.
C. A. Desoer M. Y. Wu	8/70	"Input-output properties of multiple-output discrete systems: Part II," Journal of the Franklin Institute, Vol. 290, No. 2, pp. 85-101.
C. A. Desoer	7/70	"Input-output properties of multiple-input multiple-output discrete systems," Journal of the Franklin Institute, Vol. 290, No. 1, pp. 11-24.
P. Hoff T. E. Everhart	6/70	"Carrier profiles and collection efficiency in gaussian p-n junctions under electorn beam bombardment," IEEE Trans. on Electron Devices, Vol. ED-17, No. 6, pp. 458-465.

C. W. Turner	6/70	"Acoustoelectric device applications of piezoelectric and semiconducting thin films," The Journal of Vacuum Science and Technology, Vol. 7, No. 2, pp. 534-536.
O. R. Wood S. E. Schwarz	6/70	"Study of fluorescent lifetime of the v_3 vibrational mode in SF_6," Applied Physics Letters, Vol. 16, No. 12, pp. 518-520.
W. Chou H. Frank	5/70	"Survivable communication networks and the terminal capacity matrix,:" IEEE Trans. on Circuit Theory, Vol CT-17, No. 2, pp. 192-197.
W. Y. Dere D. J. Sakrison	5/70	"Berkeley array processor," IEEE Trans on Computers, Vol. C-19, No. 5, pp. 444-447.
C. A. Desoer B. Peikari	5/70	"Design of linear time-varying and nonlinear time-invariant networks," IEEE Trans. on Circuit Theory, Vol. CT-17, No. 2, pp. 233-240.
C. A. Desoer B. Peikari	5/70	"The 'frozen operating point' method of small-signal analysis," IEEE Trans. on Circuit Theory, Vol. CT-17, No. 2, pp. 258-261.
K. L. Doty H. Frank	5/70	"Discrete-time systems with the decomposition property," IEEE Trans. on Computers, Vol. C-19, No. 5, pp. 412-420.
H. Kawamoto W. G. Oldham	5/70	"Annealing of lifetime damage in neutron-irradiated silicon," Applied Physics Letters, Vol. 16, No. 9, pp. 346-348.
A. R. Bergen R. L. Franks	2/70	"On periodic responses of nonlinear feedback systems," IEEE Trans. on Automatic Control, Vol. AC-15, No. 1, pp. 146-147.
E. P. F. Kan	2/70	"On the stability of saturating nonlinear feedback systems," IEEE Trans. on Automatic Control, Vol. AC-15, No. 1, p. 140.

D. J. Sakrison	1/70	"The rate of a class of random processes," IEEE Trans. on Information Theory, Vol. IT-16, No. 1, pp. 10-16.
E. Wong	1/70	"The distribution of intervals between zeros for a stationary Gaussian process," SIAM Journal on Applied Mathematics, Vol. 18, No. 1, pp. 67-73.
R. A. Abbott T. I. Kamins	1970	"Sodium migration through electron-gun evaporated Al_2O_3 and double layer Al_2O_3-SiO_2 structures," Solid-State Electronics, Vol. 13, pp. 565-576.
D. J. Sakrison R. J. McAuley V. C. Tyree J. Yuen	12/69	"An adaptive receiver implementation for the Gaussian scatter channel," IEEE Trans. on Communications Technology, Vol. COM-17, No. 6, pp. 640-648.
I. T. Frisch N. P. Shein	11/69	"Necessary and sufficient conditions for realizability of vertex-weighted communication nets," IEEE Trans. on Circuit Theory, Vol. CT-16, No. 4, pp. 496-502.
M. Goldstein H. Frank	11/69	"Stability criteria for nonlinear RLC networks, " Journal of the Franklin Institute, Vol 288, No. 5, pp. 351-366.
Y. Sun I. T. Frisch	11/69	"A general theory of commutated networks," IEEE Trans. on Circuit Theory, Vol. CT-16, No. 4, pp. 502-508.
H. Frank	10/69	"Analysis and optimization of disk storage devices for time sharing systems," Assoc. of Computing Machinery, Vol. 16, No. 4, pp. 602-620.
O. R. Wood P. L. Gordon S. E. Schwarz	10/69	"Saturation of infrared absorption in gaseous molecular systems," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 10, pp. 502-513.
E. R. Lewis T. E. Everhart Y. Zeevi	9/69	"Studying neural organization in Aplysia with the scanning electron microscope," Science, Vol. 156, pp. 1140-1143.

D. J. Sakrison	9/69	"Addendum to 'the rate distortion function of a Gaussian process with a weighted-square error criterion'," IEEE Trans. on Information Theory, Vol. IT-15, No. 5, pp. 610-611.
D. J. Sakrison	9/69	"An extension of the theorem of Kac, Murdock, and Szegö to N dimensions," IEEE Trans. on Information Theory, Vol. IT-15, No. 5, pp. 608-610.
C. W. Turner	9/69	"The role of acoustic wave amplification in the emission of microwave noise from InSb," IBM Journal of Research and Development, Vol. 13, No. 5, pp. 611-615.
H. Frank M. El Bardai	8/69	"Dynamic communication networks with capacity constraints," IEEE Trans. on Communications Technology, Vol COM-17, No. 4, pp. 432-437.
H. Frank	8/69	"Shortest paths in probabilistic graphs," Operations Research, Vol. 17, No, 4, pp. 583-599.
G. W. Hong J. R. Whinnery	7/69	"Switching of phase-locked states in the intracavity phase-modulated He-Ne laser," IEEE Journal of Quantum Electronics, Vol. QE-5, No. 7, pp. 367-376.
J. P. Taran T. K. Gustafson	7/69	"Comments on the self-focussing of short light pulses," IEEE Journal of Quantum Electronics, Vol QE-5, No. 7, pp. 381-382.
P. L. Gordon S. E. Schwarz C. V. Shank O. R. Wood	4/69	"Continuous infrared parametric amplification in a saturable absorber," Applied Physics Letters, Vol. 14, No. 8, pp. 235-237.
R. J. McAulay L. P. Seidmen	3/69	"A useful form of the Brankin lower bound and its applications to PPM threshold analysis," IEEE Trans. on Information Theory, Vol, IT-15, No. 2, pp. 273-279.

T. K. Gustafson R. A. Fisher P. L. Kelley	2/69	"Subpicosecond pulse generation using the optical Kerr effect," Applied Physics Letters, Vol. 14, No. 4, pp. 140-143.
D. T. Tuma A. J. Lichtenberg A. W. Trivelpiece	1969	"Electron cyclotron interaction in a magnetic mirror compression experiment," Plasma Physics, Vol. 11, pp. 117-120.
Y. Sun I. T. Frisch	12/68	"Analysis and synthesis of AC compensation filters," IEEE Trans. on Circuit Theory, Vol. CT-15, No. 4, pp. 341-349.
S. Wang	11/68	"Interferometric measurement of dielectric properties of solids," Journal of Applied Physics, Vol. 39, No. 12, pp. 5810-5811.
L. W. Davis	10/68	"Effects of transverse mode selection on the wavefront of a ruby laser," Journal of Applied Physics, Vol. 39. No. 11, pp. 5331-5332.
G. W. Hong	9/68	"Mode-coupling effects in mode-selection experiments," Journal of Applied Physics, Vol. 39, No. 10, pp. 4754-4756.
S. E. Schwarz	9/68	"Theory of an optical pulse generator," IEEE Journal of Quantum Electronics, Vol. QE-4, No. 9, pp. 509-514.
L. M. Silverman	9/68	"Synthesis of impulse response matrices by internally stable and passive realizations," IEEE Trans. on Circuit Theory, Vol. CT-15, No. 3, pp. 238-245.
Y. Sun I. T. Frisch	9/68	"Resistance multiplication in integrated circuits by means of switching," IEEE Trans. on Circuit Theory, Vol. CT-15, No. 3, pp. 184-192.
C. W. Turner	8/68	"Microwave emission from indium antimonide stimulated by acoustic wave amplification," Journal of Applied Physics, Vol. 39, No. 9, pp. 4246-4254.

C. A. Desoer M. Y. Wu	7/68	"Stability of multiple-loop feedback linear time-invariant systems," Journal of Mathematical Analysis and Applications, Vol. 23, No. 1, pp. 121-129.
P. Barfort E. R. Arquilla	6/68	"Resistance changes in lipid bilayers: immunological Applications," Science, Vol. 160, pp. 119-1121.
E. R. Lewis	6/68	"Using electronic circuits to model simple neuroelectric interactions," Proc. of IEEE, Vol. 56, No. 6, pp. 931-149.
J. K. Nakamura S. E. Schwarz	6/68	"Synchronous detection versus pulse-counting for sensitive photomultiplier detection Systems," Applied Optics, Vol. 7, p. 1073.
C. W. Turner D. R. Bryson	6/68	"Circuit-controlled modes of acoustoelectric oscillations in piezoelectric semiconductors," Electronic Letters, Vol. 4, No. 13, p. 1.
M. B. Klein	5/68	"Spectroscopic studies of the argon ion laser discharge in the vacuum ultraviolet," IEEE Journal of Quantum Electronics, Vol. QE-4, pp. 356-357.
N. C. MacDonald T. E. Everhart	4/68	"Selective electron-beam irradation of metal-oxide-semiconductor structures," Journal of Applied Physics, Vol. 39, No. 5, pp. 2433-2447.
O. R. Wood S. E. Schwarz	4/68	"Passive mode-locking of a CO_2 laser," Applied Physics Letters, Vol. 12, No. 8, pp. 263-265.
S. H. Lin K. K. Mei	3/68	"Numerical solution of dipole radiation in a compressible plasma," IEEE Trans. on Antennas and Propagation, Vol AP-16, No. 2, pp. 235-241.
S. Wang C. C. Chang	3/68	"Coherent fluorescence from zinc sulfide executed by two-photon absorption," Applied Physics Letters, Vol. 12, No. 5, pp. 193-195.

D. Eggert P. P. Varaiya	12/67	"Affine dynamical systems," Journal of Computer and System Sciences, Vol. 1, No. 4, pp. 330-348.
J. A. Byers	10/67	"Large amplitude stabilization of flute growth," The Physics of Fluids, Vol. 10, No. 10, pp. 2235-2244.
R. F. W. Pease	10/67	"The scanning electron microscope," IEEE Spectrum, Vol 4, No. 10, pp. 96-102.
D. J. Sakrison	10/67	"The use of stochastic approximation to solve the system identification problem," IEEE Trans. on Automatic Control, Vol AC-12, No. 5, pp. 563-567.
N. C. MacDonald T. E. Everhart	8/67	"Scanning electron microscope investigation of planar diffused p-n junction profiles near the edge of a diffusion mask," Journal of Applied Physics, Vol. 38, No, 9, pp. 3685-3692.
A. Sokoloff T. L. Hayes R. F. W. Pease M. Ackermann	7/67	"Tribolium castaneum: morphology of 'sureate' revealed by the scanning electron microscope," Science, Vol. 157, No. 3787, pp. 443-445.
O. R. Wood S. E. Schwarz	7/67	"Passive Q-switching of a CO_2 laser," Applied Physics Letters, Vol. 11, No. 3, pp. 88-89.
J. A. Byers	6/67	"A nonlinear computer model applicable to low-beta plasma interchange modes in two dimensions," Journal of Computation Physics, Vol 1, No. 4, pp. 496-516.
D. G. Lampard G. A. Rigby	6/67	"The application of a postive immittance inverter to the design of integrated selective filters,"Proc, IEEE, Vol. 55, No.6, pp. 1101-1102.
H. Frank	4/67	"Dynamic communication networks," IEEE Trans. on Communication Technology, Vol. COM-15, No. 2, pp. 156-163.

W. G. Oldham R. Holmstrom	4/67	"The growth and etching of Si through windows in SiO_2," Journal of the Electrochemical Society, Vol. 144, No. 4, pp. 381-388.
A. C. Soudack	3/67	"The construction of resonance curves for undamped nonlinear systems," IEEE Trans. on Education, Vol. E-10, No. 1, pp. 25-28.
S-Y. Chai P. O. Vogelhut	2/67	"Hall effect in dielectric media: microwave x-band Faraday rotation of water adsorbed on hemoglobin," Journal of Applied Physics, Vol. 38, No. 2, pp. 613-618.
E. P. Ippen	2/67	"Diffraction of light by surface acoustic waves," Proc. IEEE, Vol. 55, No. 2, pp. 248-249.
A. C. Soudack L. Zien	2/67	"Approximate solutions to Langmuir's equations," Journal of Applied Physics, Vol. 38, No. 2, pp. 889-890.
P. P. Varaiya	2/67	" Nonlinear programming in Banach space," SIAM Journal Appl. Math., Vol. 15, No. 2, p. 284-293.
W. G. Howard D. O. Pederson	1/67	"Integrated voltage controlled oscillators," Proc NEC, Vol. XXIII, pp. 279-284.
A. J. Lichtenberg P. Govindan J. R. Woodyard	1/67	"Microwave loss in a reflex plasma discharge," Journal of Applied Physics, Vol. 38, No. 1, pp. 382-389.
S. E. Schwarz T. Y. Tan	1/67	"Wave interactions in saturable absorbers,: Applied Physics Letters, Vol. 10, No. 1, pp. 4-7.
M. Orentlicher P. O. Vogelhut	12/66	"Structure and properties of liquid water," The Journal of Chemical Physics, Vol. 45, No. 12,pp. pp. 4719-4724.
R. F. W. Pease T. L. Hayes A. S. Camp N. M. Amer	12/66	"Electron microscopy of living insects," Science, Vol. 154, No. 3753, pp. 1185-1186.

D. Solimini	12/66	"Accuracy and sensitivity of the thermal lens method for measuring absorption," Applied Optics, Vol. 5, ppl 1931-1939.
S. Chai P. Vogelhut	11/66	"Method of detecting small angles of microwave Faraday ratation," Rev. Sci. Instru., Vol. 37, No. 11, pp. 1620-1621.
T. E. Everhart	10/66	"Deflection-modulation CRT display," Proc IEEE, Vol. 54, No. 10, pp. 1480-1482.
P. P. Varaiya	10/66	"Bounded-input/bounded-output stability for the Lur'e problem," IEEE Trans. on Automatic Control, Vol. AC-11, No. 4, pp. 745-746.
A. A. Gaash R. S. Pepper D. O. Pederson	9/66	"Design of integrable de-sensitized frequency selective amplifiers," IEEE Journal of Solid-State Circuits, Vol. SC-1, No. 1, pp. 29-35.
G. A. Rigby	9/66	"Integrated selective amplifiers using frequency translation," IEEE Journal of Solid-State Circuits, Vol. SC-1, No. 1, pp. 39-44.
A. C. English	8-9/66	"Physical investigation of the mesoplasma in silicon," IEEE Trans. on Electron Devices, Vol. ED-13, No. 8/9, pp. 662-667.
C. T. Chen C. A. Desoer A. Niederlinski	7/66	"Simplified conditions for controllability and observa-bility of linear time-in-variant systems," IEEE Trans. on Automatic Control, Vol. AC-11, No. 3, pp. 613-614.
C. E. Frank	7/66	"Weak magnetic field measurement using permalloy-film UHF resonance," Rev. Sci. Instru., Vol 37, No. 7, pp. 875-880.
S. E. Schwarz A. Pine	7/66	"Raman lasers using secondary Raman lines," Applied Physics Letters, Vol. 9, No. 1, pp. 49-51.

D. Solimini	7/66	"Loss measurement of organic material at 6328 Å," Journal of Applied Physics, Vol. 37, No, 8, pp. 3314-3315.
E. P. Ippen	6/66	"Electro-optic deflection with $BaTiO_3$ prisms," IEEE Journal of Quantum Electronics, Vol. QE-2, No. 6, p. 152.
R. F. W. Pease T. L. Hayes	6/66	"Scanning electron microscopy of biological material," Nature, Vol. 210, No. 5040, p. 1049.
J. A. Byers	5/66	"Confined and nonconfirmed interchange instabilities obtained form nonlinear computer models," Physics of Fluids, Vol. 9, No. 5, pp. 1038-1040.
J. Frey C. K. Birdsall	4/66	"Instabilities in a neutralized electron stream in a finite-length drift tube," Journal of Applied Physics, Vol. 37, No. 5, pp. 2051-2061.
A. Gill J.P. Jacob	4/66	"On a mapping polynomial for Galois fields," Quarterly of Applied Mathematics, Vol. XXIV, No. 1, pp. 57-62.
J. P. Jacob E. Polak	4/66	"On the inverse of the operation," American Mathematical Monthly, Vol. 73, No. 4, Part 1, pp. 388-390.
Y. T. Chan E. S. Kuh	3/66	"A general matching theory and application to tunnel diode amplifiers," IEEE Trans. on Circuit Theory, Vol. CT-13, No. 1, pp. 6-18.
A. Hasegawa	1/66	"Ion cyclotron instabilities in a bounded beam-plasma system," Japanese Journal of Applied Physics, Vol. 5, No. 1, pp. 105-112.
A. J. Lichtenberg S. Sesnic	1/66	"Absolute radiation standard in the far infrared," Optical Society of America, Vol. 56, No. 1, pp. 75-79.

T. E. Everhart	1966	"Certain semiconductor applications of the scanning electron microscope," The Electron Microphone, pp. 665-676.
D. J. Sakrison	1966	"Stochastic approximation: A recursive method for solving regression problems," Adv. in Communications Systems, Vol. 2.
P. P. Varaiya R. Lin	1966	"Bounded-input bounded-output stability of nonlinear time-varying differential systems," SIAM Journal on Control, Vol. 4, No. 4, pp. 698-704.
J. P. Jacob	12/65	"The number of terms in the general gain formulas for Coates and Mason signal flow graphs," IEEE Trans. on Circuit Theory, Vol. CT-12, No. 4, pp. 601-604.
K. R. Swaminathan I. T. Frisch	12/65	"Necessary conditions for the realizability of N-port resistive networks with more than (n+1) nodes," IEEE Trans. on Circuit Theory, Vol. CT-12, No. 4, pp. 520-527.
N. C. MacDonald	11/65	"Direct measurement of the depletion layer width variation vs applied bias for a P-N junction," Applied Physics Letters, Vol. 7, No. 19, pp. 267-269.
C. T. Chen	10/65	"On the stability of nonlinear sampled-data feedback systems" Journal of the Franklin Institute, Vol. 280, No. 4, pp. 316-324.
E. Wong M. Zakai	10/65	"On the convergence of ordinary integrals to stochastic integrals," The Annals of Mathematical Statistics, Vol. 36, No. 5, pp. 1560-1564.
J. Frey C. K. Birdsall	9/65	"Electron stream diode instabilities with elastic collision Journal of Applied Physics, Vol. 36, No. 9, pp. 2962-2964.

E. S. Kuh R. A. Rohrer	7/65	"The state-variable approach to network analysis," Proc. IEEE, Nol. 53, No. 7, pp. 672-686.
A. J. Lichtenberg D. Tuma	7/65	"Synchrotron radiation from a self-consistent plasma," Physics of Fluids, Vol. 8, No. 7.
R. M. White	7/65	"Monochromatic illumination of cadmium-sulfide oscillator," Proc, IEEE, Vol. 53, No. 7.
E. S. Kuh	6/65	"Stability of linear time-varying networks -- The state space approach," IEEE Trans. on Circuit Theory, Vol. CT-12, No. 2, pp. 150-157.
E. Wong M. Zakai	6/65	"On the relation between ordinary and stochastic differential equations," International Journal of Engineering Science, Vol. 3, pp. 213-229, and Proc. Third IFAC Congress.
L. A. Zadeh	6/65	"Fuzzy sets," Information and Control, Vol. 8, No. 2, pp. 338-353.
W. B. Bridges J. I. Frey C. K. Birdsall	5/65	"Limiting stable currents in bounded electron and ion streams," IEEE Trans. on Electron Devices, Vol. ED-12, No. 5, pp. 264-272.
B. W. Jordan E. Polak	4/65	"Optimal control of aperiodic discrete-time systems," SIAM Journal on Control, Ser. A, Vol. 2, No. 3.
M. L. Conragan R. S. Muller	3/65	"Hexagonal $CdCl_2$ deposits on HCl-etched CdS films," Solid-State Electronics, Vol. 8, No. 10, pp. 830.
C. W. Ho I. T. Frisch	3/65	"A unified theory of synthesis with unsymmetric four-element lossless lattices," IEEE International Convention Record, 1965, pp. 147-158.

A. Baghdasarian	2/65	"Solution of circular loop antennas and scattering from conducting loops by numerical methods," Proc. IEEE, Vol. 53, No. 8, pp. 818-822.
A. J. Lichtenberg J. S. Jayson	2/65	"Propagation and instabilities of waves in bounded finite temperature plasmas," Journal of Applied Physics, Vol. 36, No. 2, pp. 449-455.
K. K. Mei M. Moberg	2/65	"Measurement of surface current distribution on cylindrical obstacles," Proc. IEEE, 1965.
K. Mouthaan	1/65	"Wave-mechanical approach to the nonlinear theory of O-type travelling-wave tubes," International Journal of Electronics, Vol. 18, No. 4, p. 301.
J. E. Scharer A. W. Trivelpiece	1/65	"Quasistatic analysis of waves in a plasma-filled waveguide," Journal of Applied Physics, Vol. 36, No. 1, pp. 318-319.
A. Chang	1965	"An optimal regulator problem," SIAM Journal on Control, Ser. A, Vol. 2, pp. 220-233.
M. A. Harrison	1965	"A census of finite automata," Can. J. Math., Vol. 17, pp. 100-113.
T. Y. Chang	11/64	"Laser-induced emission of electrons, ions, and neutrals from Ti and Ti-D surfaces," Applied Physics Letters, Vol. 5, No. 9, pp. 171-172.
A. Hasegawa C. K. Birdsall	10/64	"Fast-acting valve which operates at temperatures up to 400° C," Rev. Sci. Instru., Vol. 35, No. 10, pp. 1362-1363.
G. E. Bodway S. Wang	9/64	"Instabilities in the magnetization vector in YIG at high microwave power levels," Journal of Applied Physics, Vo. 36, No. 8, pp. 2566-2568.

A. J. Lichtenberg S. Sesnic A. W. Trivelpiece	9/64	"Measurements of the synchrotron radiation spectrum from a hot plasma," Physics Review Letters, Vol. 13, No. 13, pp. 387-388.
A. J. Lichtenberg S. Sesnic A. W. Trivelpiece	9/64	"Synchrotron radiation measurements from a plasma in a magnetic mirror machine," Physics of Fluids, Vol. 7, No. 9.
I. T. Frisch	8/64	"A stability criterion for tunnel diodes," Proc. IEEE, Vol. 52, No. 8. pp. 922-923.
V. Galindo	7/64	"Design of dual-reflector antennas with arbitrary phase and amplitude distribution," IEEE Trans. on Antennas and Propagation, Vol. AP-12, No. 4, pp. 403-408.
R. N. Carlile	5/64	"A backward-wave surface mode in a plasma waveguide," Journal of Applied Physics, Vol. 35, No. 5, pp. 1384-1391.
E. Wong	4/64	"A linear search problem," SIAM Review, Vol. 6, No. 2, pp. 168-174.
D. O. Pederson G. H. Wilson	3/64	"Dominant zero and excess phase of a Hurwitz polynomial," IEEE Trans. on Circuit Theory, Vol. CT-11, No. 1, pp. 104-108.
E. Polak	1/64	"A note on D-decomposition theory," IEEE Trans. on Automatic Control, Vol. AC-9, No. 1, pp. 107-109.
S. C. Parikh I. T. Frisch	12/63	"Finding the most reliable routes in communication systems," IEEE Trans. on Computer Science, Vol. CS-11, No. 4, pp. 402-406.
E. Polak H. Kwakernaak	12/63	"On the reduction of the system $x = Bx + Bu$, $y + c'x$ to its minimal equivalent," IEEE Trans. on Circuit Theory, Vol. CT-10, No. 4, pp. 139-163.

C. T. Lee C. A. Desoer	10/63	"Fuel optimal control for pulse-amplitude-modulated time-invariant sampled-data system," Journal Electronics and Control, Vol. 15, No. 4, p. 363 (also Electronics Res. Lab. Tech. Report No. 60-447)
I. T. Frisch	6/63	"Optimum routes in communication systems with channel capacities and channel reliabilities," IEEE Trans. on Computer Science, Vol. CS-11, No. 2, pp. 241-246.
A. Paige C. A. Desoer	6/63	"Linear time-varying GC networks: stable and unstable," IEEE Trans. on Circuit Theory, Vol. CT-10, No. 2, pp. 1962-1964.
I. T. Frisch	5/63	"Optimization of communication nets with switching," Journal of the Franklin Institute, Vol. 275, No. 5, pp. 404-430.
S. Wang S. Yee K. Nosaka	5/63	"Radiative recombination through tunneling in Ge mesa transistors," IEEE Trans. on Electron Devices, Vol. ED-10, No. 3, p. 1.
S. Wang S. Yee K. Nosaka	4/63	"Direct radiative recombination in Ge mesa transistor," Journal of Applied Physics, Vol. 2, No. 8, pp. 149-150.
I. T. Frisch	3/63	"Communication systems of channels with bounded non-decreasing costs per unit of information flow," IEEE Trans. on Computer Science, Vol. 11, No. 1, pp. 36-40.
R. S. Pepper	3/63	"Minimum period of electronic oscillators," IEEE Trans. on Circuit Theory, Vol. CT-10, No. 1, pp. 60-66.
S. C. Gupta L. Hasdorff	12/62	"Changing the state of a linear system by use of normal function and its derivatives," Journal Electronics Control.

S. Wang G. E. Bodway	12/62	"Relaxation oscillation near the threshold of instability in yttrium iron garnet, Journal of Applied Physics, Vol. 33, No. 12- pp. 3526-3528.
S. Kodama	10/62	"Stability of a class of discrete control systems containing nonlinear-gain element," IRE Trans. on Automatic Control, Vol. AC-7, p. 102.
I. Cederbaum	9/62	"Applications of graph theory to solution of some systems of linear algebraic equations," Matrix and Tensor Quarterly, (Brit.).
I. Cederbaum	8/62	"On optimal operation of communication nets, Journal of the Franklin Institute, Vol. 274, pp. 130-141.
P. Elias A. Gill L. A. Zadeh et al.	7/61	"Progress in information theory in the U.S.A., 1957-1960; prediction and filtering," IRE Trans. on Information Theory, Vol. IT-7, No. 3, pp. 128-144.
C. A. Desoer	5/61	"A minimal time discrete system," IRE Trans. on Automatic Control, Vol. AC-6, No. 2, pp. 111-125.

University of California, Berkeley — Electronics Research Laboratory

Joint Services Electronics Program — September 30, 1980

Work Unit No.: ISS-81-5(terminating in part) — Last Year's No.(s): ISS-80-5

Title: Analog Adaptive Filters for Speech Processing

Senior Principal Investigator(s): R. W. Brodersen (415) 642-1779
D. G. Messerschmitt 2-1090

Scientific Objectives

The long term objective of this research is to achieve a dramatic reduction in the complexity of certain signal processing functions implemented in MOS integrated circuit technology. In particular, analog sampled data and switched capacitor filters will be used for realizing certain non-adaptive and adaptive filters which have previously been realized by digital recursive and transversal filter structures. To achieve this goal, the adaptive filtering algorithms used heretofore will have to be fundamentally restructured. Specific attention will be directed at applications in speech processing, including analysis, synthesis, and recognition of speech.

State of the Art

This proposal touches on several diverse areas of past research, including algorithms for the analysis, synthesis, and recognition of speech, as well as the implementation of signal processing algorithms.

Methods of synthesis of speech are closely tied to the corresponding analysis method, so we concentrate on the latter here. Speech analysis has been attempted by representation with suitable basis functions[1,2] and by short-time spectral analysis techniques[2-12]. The latter, which have been more successful and much more extensively pursued, include the channel vocoder[2-4,10], estimation of format frequencies by Fourier transform techniques[2,5,6], and the homomorphic vocoder[9,10,11]. The channel vocoder is usually, but not always, implemented by a bank of bandpass filters, while the remaining techniques are almost always implemented digitally. Gold[10] gives an excellent summary of the current state of the art in digitally implemented vocoders. A typical complexity for an implementation with general purpose devices is about 150 integrated circuits, with a speed of operation consistent with only high speed bipolar logic families.

In LPC, which has been extensively investigated because of its very efficient representation of the vocal tract parameters, it is most common to derive the predictor coefficients or reflection coefficients on a block basis using recursive algorithms[8,10]. However, it is also possible to update predictor coefficients continuously in time by an adaptive gradient algorithm similar to that used in adaptive noise cancelling[12].

A typical speech recognition system is composed of three separate functional blocks[13,14,15]. The first block is the signal processing front end which attempts to represent the speech in terms of a minimal set of parameters, such as the LPC coefficients discussed earlier. Second, a measure of the similarity between the speech sound being analyzed and a set of templates is calculated. Finally, a matching technique is used to determine the template which best fits the speech sound.

The two parts of a speech recognition system which are most complex are the front end speech processing and the template matching[13].

Previous Work at Berkeley

At Berkeley a variety of analog integrated circuits have been developed[16-20]

to perform specific signal processing functions. These circuits include A/D converters, multiplying D/A converters, and a variety of approaches to monolithic MOS filtering. The most successful development in the latter category has been the switched capacitor filter technique, with which low pass, band pass, and high pass filters can be implemented. These filters require a small silicon area, and thus can be fabricated on the same integrated circuit with other analog and digital circuitry.

In addition, at this time there is an on-going effort in applications of MOS-LSI to low cost implementations of narrow band vocoding. This research is concerned with applying the new MOS analog sampled data techniques to the implementation of existing speech processing algorithms[21]. This effort will complement the research proposed here, which is concerned with developing entirely new algorithms to more fully exploit the capabilities of MOS-LSI, particularly as it is expected to evolve into VLSI in the future.

Progress and Publications

A. Under JSEP

A new generalized form of the lattice filter in which the delay element has been replaced by an arbitrary all-pass filter has been discovered. This has been written up in the following paper, which has been accepted for publication: D. G. Messerschmitt, "A Class of Generalized Lattice Filters," IEE Trans. Accoustics, Speech and Signal Processing, April 1980.

Abstract

It is shown that the digital lattice filter utilized as a predictor in speech processing is a special case of a broad class of filters with identical properties, in which the delay element is replaced by an arbitrary analog or digital all-pass filter. The performance of three filters in this class, the delay element and single-pole analog and digital all-pass sections, are compared for the spectral estimation application. Another application is a realization of analog transfer functions in a lattice realization using a switched capacitor all-pass section.

A significant issue in the choice of an all-pass filter for the generalized lattice is the effect on filter coefficient sensitivity. This sensitivity relates directly to the bit rate required when filter coefficients are used to characterize the vocal tract in speech applications. The first step was to obtain for the first time analytical expressions for the sensitivity, which have been published in the following paper: Peter L. Chu and David G. Messerschmitt, "Zero Sensitivity of the Digital Lattice Filter," IEEE Int. Conf. on Audio, Acoustics and Signal Processing, April 1980.

Abstract

Recursive equations for the first-order zero movement sensitivities of the all-zero digital lattice filter are given. In addition to being useful for numerical evaluation, these equations allow general conclusions to be drawn concerning the quite different sensitivity properties of early and final stages. The approach differs from previous sensitivity studies, which considered measures consisting of integrals of the ratio of the deviated spectrum to the original spectrum, and is therefore more useful in directly studying the sensitivity of format bandwidth and center frequencies when the filter is used in speech synthesis.

It is planned to publish an expanded version of this paper in the ASSP Transactions in the near future.

More recently, an important new application of the generalized lattice has been found. It has been found that by choosing the all-pass filter judiciously, the sensitivity characteristics can be tailored closely to the human ear. Specifically, the low-frequency poles can be made less sensitive to filter coefficient changes, and the high frequencey poles correspondingly more sensitivie, with an attendant subjective improvement. The result should be a reduction in the bit rate required for LPC speech comparable to that previously obtained by use of pre-emphasis.

Current work in this area is concentrating on proper choice of an all-pass filter, subjective tests to confirm the benefit derived from the generalized lattice, and further understanding of the sensitivity issues. In the latter area, effort is being devoted to understanding of the sensitivity properties of other sets of parameters useful for representing the vocal tract configuration, such as autocorrelation coefficients.

The second major area of study has been application of these techniques to a speech recognition system, as well as other components of such a system including template matching.

Although template matching has been done on high speed digital computers in the past, it appears to be particularly advantageous to implement these time-consuming and regular algorithms in hardware. One particularly difficult aspect of template matching is the time alignment of the analysis information. A dynamic programing algorithm has been investigated for use in providing an optimal method of alignment and time warping. Extensive computer simulations were made to determine the performance of the algorithm. Accuracies which were achieved in these simulations were from 98-99% for a vocabulary of 50 words.

Progress and Publications, cont'd

A breadboard to simulate an integrated circuit which would implement the dynamic programing algorithm in real time was then constructed and its performance appears consistent with the computer simulations. Careful consideration of the architecture has made it possible to consider implementing the entire dynamic programing function on a single chip. Preliminary results have been reported in the following paper: H. Murveit, M. Lowry and R. W. Brodersen, "Low Cost Implementation of Speech Recognition System," Proc. of COMPCON, San Francisco, March 1980.

B. Under Other Sponsorship

Under NSF sponsorship, we are studying the application of the lattice filter to LPC and to the prediction filter in ADPCM. Of particular concern is the speed of adaptation of adaptive forms of the lattice filter, and understanding of this issue is being developed.

Also under NSF and industrial support, we are exploring various hardware implementation issues relating to adaptive filters. Recently, breadboarding has been a new approach to the implementation of an analog adaptive transversal filter and an ADPCM speech coder with adaptive quantization which uses switched-capacitor techniques.

Additional work on implementation of adaptive filters is being performed under a contract to DARPA for implementation of a low cost vocoder for secure speech transmission. These implementations use conventional algorithms instead of the new generalized lattice filters described above.

Significant Accomplishments

1. Discovery of the generalized form of the lattice filter, of interest particularly in switched-capacitor implementation.

2. The realization that the lattice filter can be used to realize arbitrary continuous-time as well as discrete-time transfer functions.

3. A simplified proof of lattice filter stability properties.

4. Understanding of the sensitivity properties of the lattice filter.

5. Extension of this sensitivity understanding to the generalized lattice filter.

6. Discovery that the generalized lattice can be used to reduce bit rate of LPC encoded speech for a fixed subjective quality.

7. Development of a hardware approach to dynamic programing time alignment in speech recognition template matching.